DEVELOPMENT OF ISOTHERMAL RIGS

FINAL REPORT

Prepared for

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SYSTEMS GROUP
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FINAL REPORT

DEVELOPMENT OF ISOTHERMAL RIGS

NASA George C. Marshall Space Center

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Prepared by:

R. A. Kaminskas
D. J. Malone

TRW
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1.0 INTRODUCTION

This report describes the Task 1 results of the Resonant Infrasonic Gauging System (RIGS) development program. The program consisted of analysis, design, fabrication, and tests of a prototype RIGS. The program was conducted under NASA, George C. Marshall Space Flight Center sponsorship, Contract NAS8-28574, between March 27, 1972 and April 9, 1973.

The RIGS is a gauging system that is capable of measuring propellant quantity under zero-g as well as under accelerated (one-g) conditions. With the exception of liquid hydrogen, it can be used to gauge virtually any propellant in liquid form including cryogenics. The gauge consists of a sensor unit which is attached to the propellant tank and electronic control unit which may be positioned separately from the sensor. The control unit receives the signals from the sensor as well as the ullage gas pressure and propellant temperature measurements, and computes the propellant quantity remaining in the tank.

The principal advantages of the RIGS over more conventional gauging systems such as PVT or capacitance systems are:

- RIGS will operate under zero-g as well as under accelerated conditions.
- Will operate with vented tanks.
- Can be used to gauge propellants in tanks using bladders, as well as bladderless tanks.
- Can be used to gauge any size or shape tanks, including most tanks incorporating surface tension propellant orientation devices.

During the course of this program two prototype RIGS sensors were designed and constructed. The sensors were tested first in the laboratory using water as the simulated propellant and, later, using LN_2 in a 100-gallon tank. The system tests proved that the gauge operates virtually as predicted by theory and yielded an accuracy better than 1%.

The specific tasks that this program attempted to accomplish are:

1. Design a RIGS sensor breadboard.

2. Fabricate the RIGS sensor.

3. Using laboratory equipment design and set up a control system to operate the RIGS sensor.

4. Test at least two candidate plastic and two metal bellows for the RIGS sensor.

5. Mount the RIGS sensor on a tank (approximately 50 gallons capacity) suspended in a gimbaled structure so that it can be rotated and perform the following tests:

   a. Change the amount of fluid in the tank from empty to full in 10% increments and rotate the tank at each fill level. Record fluid volume measurements at each 30 degrees of rotation and at any other point of rotation where the volume reading changes.

   b. Measure the effective specific heat ratio (γ) as a function of frequency using water to simulate the propellant and a mixture of N_2 and He to simulate the ullage gas. Ullage gas shall vary from 100% N_2 to 100% He with different mixture ratios in between.

   c. Measure the effect of typical surface tension screen materials as a function of RIGS resonating frequency (using water as the simulated propellant).

   d. Measure the RIGS resonating frequency with the tank at different orientations to determine the extent of pressure wave attenuation when transmitted through the propellant. Study effects on resonating frequency when the isolation diaphragm is 1/4, 1/2, and 3/4 covered by the fluid.

   e. Install the RIGS sensor on a cryogenic tank and gauge at least 10 equally spaced propellant levels with the tank in an upright position.

6. Based on laboratory test data select resonating frequencies for a RIGS applicable to Shuttle Vehicle LOX tanks and determine the effect of ullage gas parameters and surface tension screens on the RIGS accuracy. Analytically predict the RIGS performance characteristics such as response time, effect on "g" conditions and accuracy. From above tests study possibility of gauging LH_2 with this sensor.

Tasks 1, 2, and 3 were accomplished as required by the work statement. As mentioned above actually two sensors were designed and built. Also, instead of just using laboratory equipment to set up the control system, a complete control unit breadboard was designed and constructed.

Task 4. No suitable metal bellows could be found for use with the RIGS, thus only plastic bellows were used. Also it was found that several LOX compatible plastics, which were originally contemplated for use with the RIGS were not sufficiently flexible at cryogenic temperatures. As a result the RIGS was redesigned to provide thermal insulation between the sensor and the propellant so that the bellows would not be exposed to cryogenic temperatures liquids.

Task 5. The majority of the tests of Task 5 were accomplished and are described in this report, except that LN_2 was used instead of LOX, and, due to a technical difficulty with pressure equalization, the sensor was not tested upside down.

Task 6. It was found that the RIGS in the configuration tested during this program was marginal for use on spacecraft. An improved version of the RIGS, called the "Augmented RIGS", which overcomes virtually all the disadvantages of the existing version has been designed and is described in this report.

This report is subdivided into 7 sections. Section 2 is a summary of the program which briefly describes the principle of operation, hardware details, and test results. Sections 3 through 5 give detailed descriptions of the RIGS design analyses, sensor design and electronic subsystems. Section 6 describes the test results. Section 7 gives a summary and recommendations for further work.

2.0 SUMMARY

Originally the Resonant Infrasonic Gauge System (RIGS) was designed at TRW for use on the Apollo SPS tanks. The system was thoroughly analyzed and a breadboard model was constructed and tested. Although the test results were very encouraging, it became evident that the system could not be developed and qualified in time for use on the Apollo and the development was discontinued in 1967. With the advent of the Space Shuttle Vehicle, the development of the RIGS was resumed again in April 1972 as a candidate for gauging the shuttle booster LOX tank.

The RIGS schematic diagram is shown in Figure 2-1. The system consists of a sensor which is attached to the tank and an electronic control unit. Ullage gas pressure and propellant temperature measurement are also required by the control unit for fuel mass computation. The sensor, as shown in Figure 2-1, consists of a driver and a follower piston (bellows). The driver piston frequency is varied to determine the frequency at which the follower piston is in resonance with the ullage gas volume of the tank (which acts as a spring when compressed). The mass of the follower piston is sized to reduce the resonant frequency to several Hz or less. (As the fuel is depleted the ullage volume increases and the resonant frequency decreases). Use of low frequency serves two purposes:

1. The ullage gas compression occurs in a nearly isothermal mode.
2. The pressure wave is transmitted through the propellant without significant attenuation.

It is important for the RIGS to operate in essentially the isothermal mode so that the resonating frequency does not change with the constitution of the ullage gas (due to changes in the ratio of the specific heats γ). This is especially important when gauging a vented LOX tank where the ullage gas is composed of O_2 vapors and helium pressurant in a ratio that can change significantly during the course of the mission.

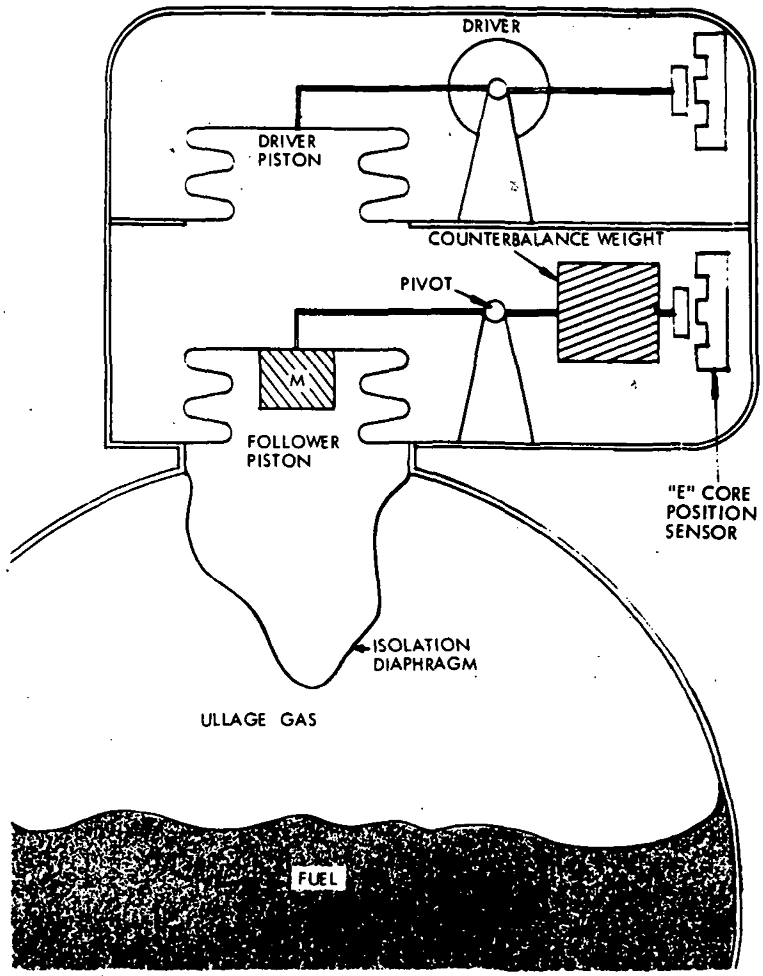

Figure 2-1. RIGS Sensor Schematic Diagram

Figure 2-1 shows an isolation diaphragm between the sensor and the tank. This diaphragm prevents the propellant from entering the sensor but is sufficiently flexible so that it can transmit the pressure waves from the follower piston without attenuation. For tests with water, a rubber bag was used as the isolation diaphragm. For tests with cryogenics, a Teflon diaphragm will be used.

The driver piston in the prototype RIGS sensors was actuated by an electric DC motor through a gear reduction and a crankshaft drive. In the future it is planned to replace the motor with an electromagnetic (loud speaker type) actuator. The piston position is measured by an "E" core position transducer, as shown in Figure 2-1. The actuating frequency of the driver is varied by the control unit to maintain a given phase

relationship between the driver and the follower pistons. Theoretically, the driver should lead the follower by a few degrees when the follower is in resonance with the ullage volume. However, in practice, it was found that best results were obtained at considerably larger phase differences (on the order of 25 degrees).

The Control unit block diagram is shown in Figure 2-2. It receives the driver and follower piston position signals, computes the phase difference between them and adjusts the driver motor speed to keep the phase at the desired value.

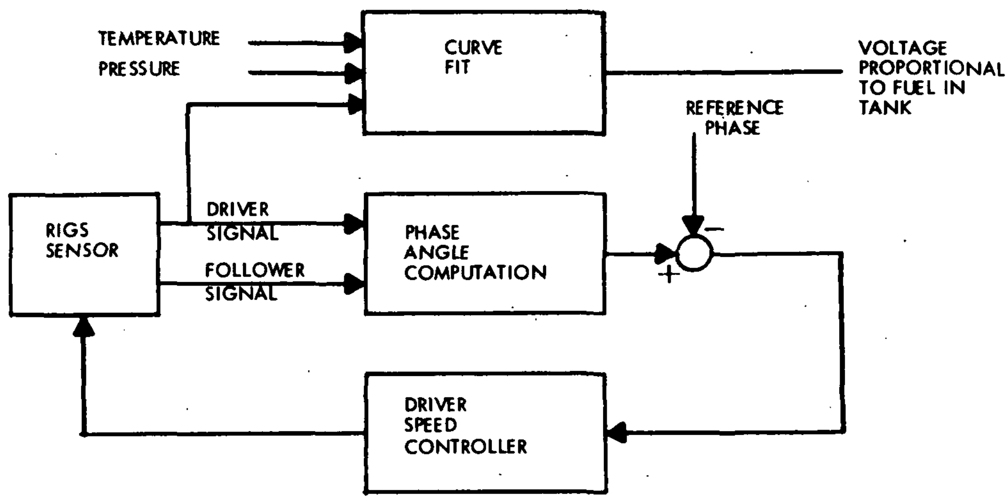

Figure 2-2. RIGS Control System Block Diagram

Two prototype RIGS sensors were built. They are shown in Figures 2-3 and 2-4. The sensor in Figure 2-3 was made out of Plexiglas so that the driver and follower piston motion could be observed and studied. The second sensor, shown in Figure 2-4, was built for tests with cryogenic propellants. The control system, which was used with both sensors, is shown in Figure 2-5.

Some of the test data obtained with the RIGS are given in Figure 2-6. It can be seen that the sensor performance was very close to the predicted values and the system gave an overall gauging accuracy better than 1.0%.

Figure 2-3. RIGS Sensor (First Unit)

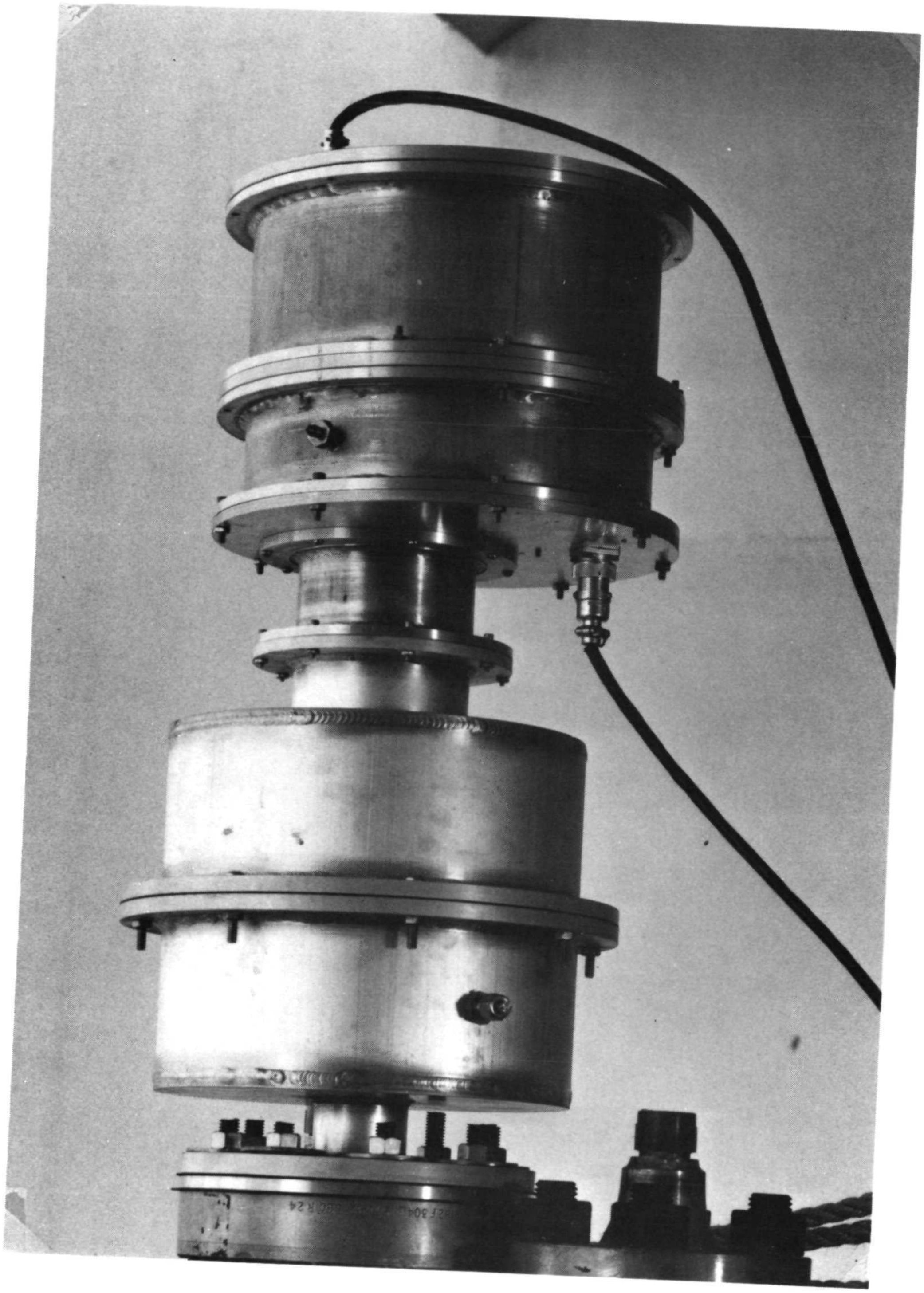

Figure 2-4. RIGS Sensor (Second Unit)

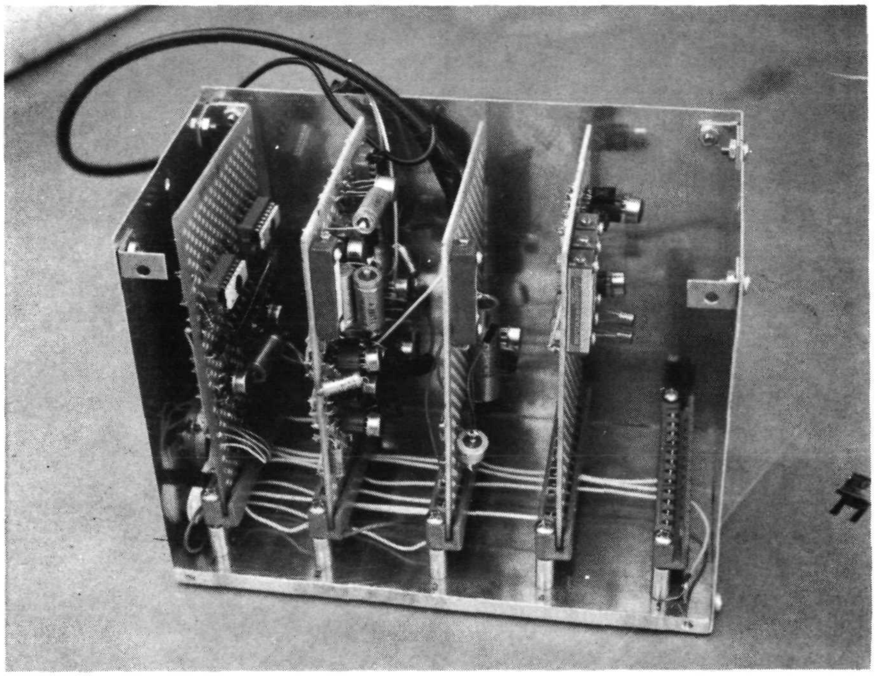

Figure 2-5. RIGS Control System Electronics

This phase of the program proved the feasibility of the RIGS. However, some additional design improvements are required before the system is ready for final development and subsequent use to gauge propellant quantity onboard the Shuttle vehicle and/or other spacecraft. The three principal design areas are described below along with a promising design solution:

1. In order to have a low enough RIGS resonating frequency, the follower bellows must be weighted with about a one pound mass which in turn requires the use of another one pound counterbalance. This weight combined with the low friction requirement makes it difficult to design a system that is both strong and rigid enough to take the launch vibration and acceleration requirements.

2. The follower piston bellows requires a spring constant of less than 0.1 lb per inch. This makes the bellows very flimsy and difficult to handle.

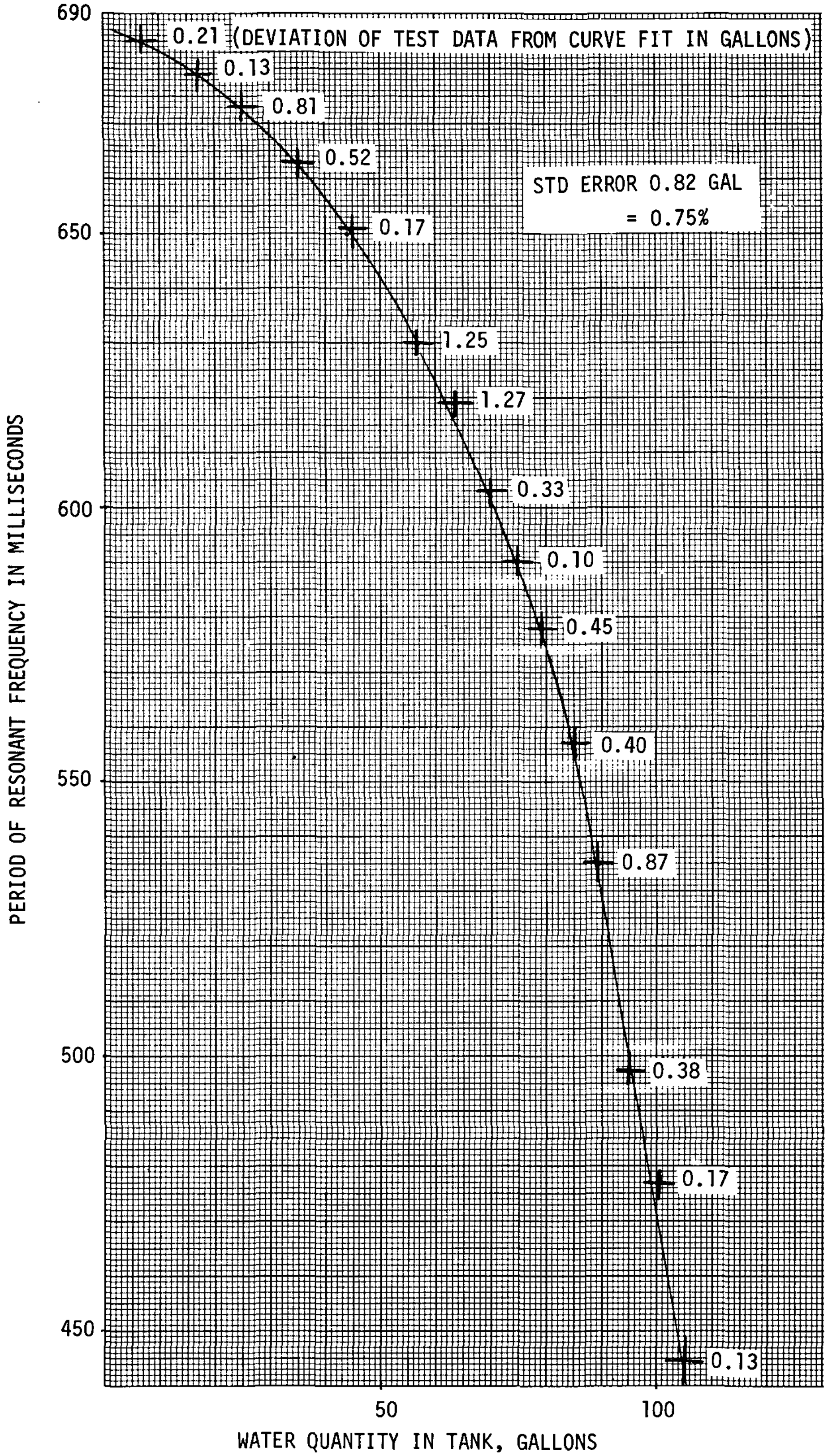

Figure 2-6. RIGS Test Data

3. The present version of the RIGS control system requires on the order of 30 seconds to stabilize sufficiently to measure the resonant frequency. This response time appears to be much too slow to be practical if the gauge is used for Propellant Utilization (PU) purposes or other transient conditions.

The first two disadvantages of the present system can be corrected by augmenting the RIGS with an electronic subsystem which eliminates the requirement of a heavy mass on the follower piston and allows the use of considerably more rigid bellows. In essence, the ullage volume of the tank would resonate with an electronic circuit, rather than a physical mass, thereby considerably simplifying the sensor hardware design. The third problem area is automatically solved by going to the electronically-augmented version of the RIGS and redesign of the front end of the control system. The tasks for further development and a description of the Augmented RIGS concept are described in detail in Section 7.0.

3.0 PRINCIPLE OPERATION OF RIGS

The operating components of the RIGS system are presented schematically in Figure 3-1. The system is comprised of three basic elements, viz.,

1) a driver piston
2) a follower piston or diaphragm, and
3) a variable frequency driver.

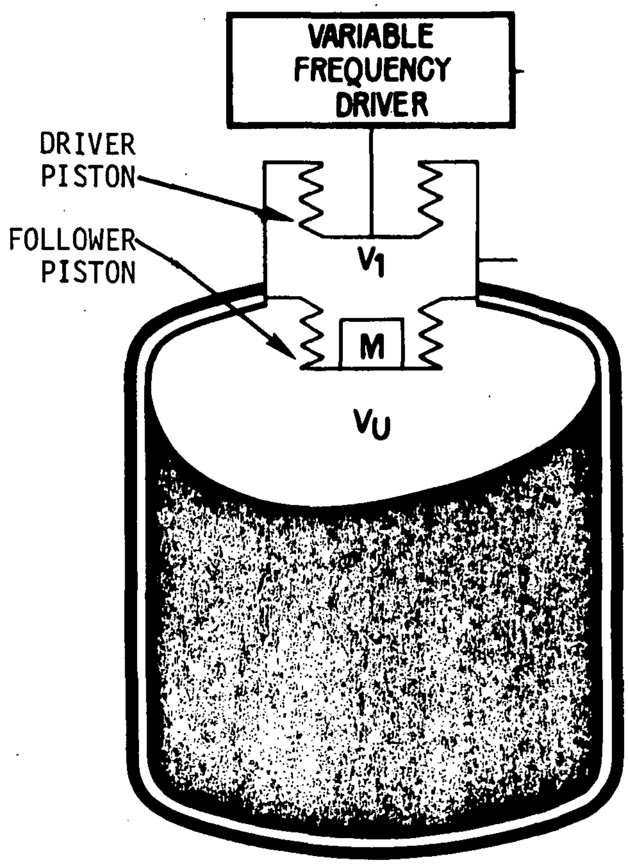

Figure 3-1. RIGS Schematic

From the arrangement shown, a downward motion of the driver piston will produce a volume displacement in V_1 causing the follower piston to move a corresponding distance; in turn, the follower piston compresses the ullage. If the driver is moved sufficiently slowly such that dynamic effects can be ignored, then the pressure change in the ullage (assuming adiabatic conditions) is given by:

$$\frac{\Delta P}{P} = -\gamma \frac{\Delta V}{(V_u + V_1)} \cong -\gamma \frac{\Delta V}{V_u} \text{ with } V_u >> V_1 \tag{3-1}$$

where:

V_1 = volume between pistons

V_u = ullage volume

γ = ratio of specific heats.

On the other hand, if the driver is excited sinusoidally at increasing frequency, equation (3-1) is no longer valid and the dynamic effects must be taken into consideration. This is accomplished directly by noting that the follower piston is simply a mass coupled to the driver and the ullage through two gas "springs" represented respectively by the volume between the two pistons, V_1, and the ullage volume, V_u. Assuming an adiabatic process, the spring rate of the two volumes is:

$$K_1 = \gamma \frac{P_1 A^2}{V_1} \qquad K_u = \gamma \frac{P_u A^2}{V_u} \tag{3-2}$$

where:

A = area of follower piston

$P_1 = P_u$ = system static pressure.

The mechanical equivalent of the system is shown in Figure 3-2.

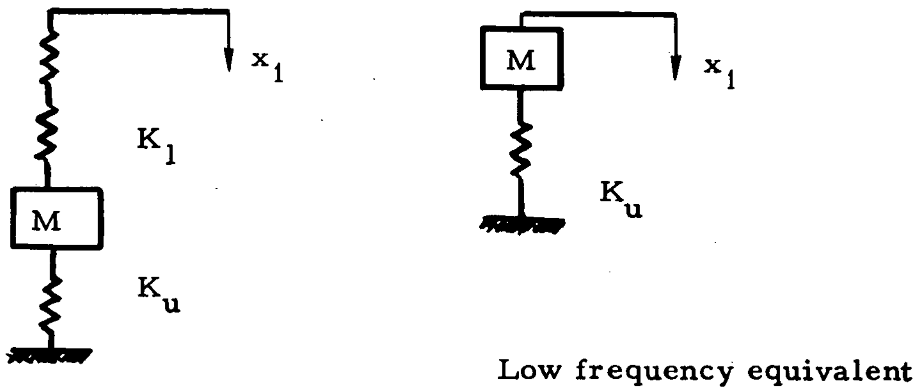

Figure 3-2. System Mechanical Equivalent

Since the ullage gas volume (V_u) is much larger than V_1, the spring rate K_1 is appreciably greater than K_u, and at low frequencies the upper volume acts essentially as if it were a stiff rod imposing a motion of the mass M (Figure 3-2). The force which must be transmitted by K_1 to produce the motion of the mass is a function of the dynamic impedance of the mass and the ullage gas spring; i.e.,

$$F_{total} = \text{Force to accelerate mass} + \text{force to compress } K_u$$
$$= F_M + F_u$$

However, since in practice the pistons are made using bellows, the spring constant of the bellows (K_B) must also be taken into account. Thus the equation above is rewritten:

$$F_{total} = F_M + F_B + F_u$$

and

$$F_{total} = M \frac{d^2x}{d\,t^2} + (K_u + K_B)X = M\ddot{x} + (\frac{A^2\gamma\ P_u}{V_u} + K_B)\ x \qquad (3\text{-}3)$$

At some particular frequency, the force required to accelerate the mass will be balanced by the restoring force of the gas spring and the system will be in resonance (i.e., in the absence of friction, the system will continue to oscillate without any additional applied force). At this

condition,

$$M\ddot{x} + \left(\frac{A^2 \gamma P_u}{V_u} + K_B\right) = 0 \qquad (3\text{-}4)$$

Solving for the resonant frequency yields:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{A^2 \gamma P_u}{M V_u} + \frac{K_B}{M}} \qquad (3\text{-}5)$$

Thus, the resonant frequency is related to the spring constant of the bellows and the magnitude of the ullage gas spring rate or the ullage volume. By knowing the mass and area of the follower piston, and the pressure and the effective specific heat ratio of the ullage gas, the ullage volume is uniquely determined by measuring the resonant frequency.

This then is the basis of the RIGS system. The resonant frequency of the follower piston is determined by demanding that the phase difference between the driver and the follower piston be of a certain value. As the driver frequency is varied, the phase difference varies between them. At the resonant point, when the driven piston mass is in resonance with the ullage gas cavity, the driver is leading the follower by a few degrees.

From the description given above it is seen that the resonating frequency of RIGS is proportional to the ullage volume and the average γ of the ullage gas. As the γ varies (with ullage gas temperature and/or composition due to addition of pressurant gas), the RIGS resonating frequency may change and can cause an error in propellant quantity measured. This, of course, assumes that the system obeys adiabatic gas laws. However, if isothermal gas laws were used, the ratio of the specific heats would approach unity and γ would not enter into the relationship. Thus there would be no error introduced due to variation of ullage gas parameters. In reality the RIGS operates somewhere between the idealized adiabatic and isothermal conditions. One may argue that if the RIGS resonating frequency is selected high compared to the heat transfer rate (assumed to be between the ullage gas and the propellant), the gas behavior will obey the adiabatic law. Low frequency will approach an isothermal condition because the propellant

will act as a heat sink and the ullage gas will tend to remain at a constant temperature during any single gauging process, and thus the effective γ will approach unity. The "real life" RIGS behavior may be explained by referring to Figure 3-3. (The ullage gas consists of propellant vapor and pressurant gas.) The average γ will be primarily affected by the composition of ullage gas. For example, using LOX as the propellant pressurized with helium, the gaseous oxygen (O_2), γ is $\sim$1.4; for helium the γ is $\sim$1.67. Thus at adiabatic conditions the γ will be somewhere between 1.4 and 1.67 depending on the O_2 to He pressurant ratio. When isothermal conditions are approached, $\gamma \rightarrow 1$ regardless of what the ullage gas ratio is. Thus if the RIGS operating frequency range is selected such that γ is close to unity, there will be no appreciable error in propellant quantity measurement due to ullage gas composition, nor other variations in ullage gas parameters.

In view of the difficulty of performing the heat transfer computations required to produce a definitive plot such as shown in Figure 3-3, an empirical approach to obtaining the necessary data to predict the RIGS error as a function of γ of the ullage gas was adopted during the program. This consisted of a test with the RIGS sensor attached to a tank filled with fluid. To vary the γ of the ullage gas, various gases and/or mixtures were used to pressurize the system. By

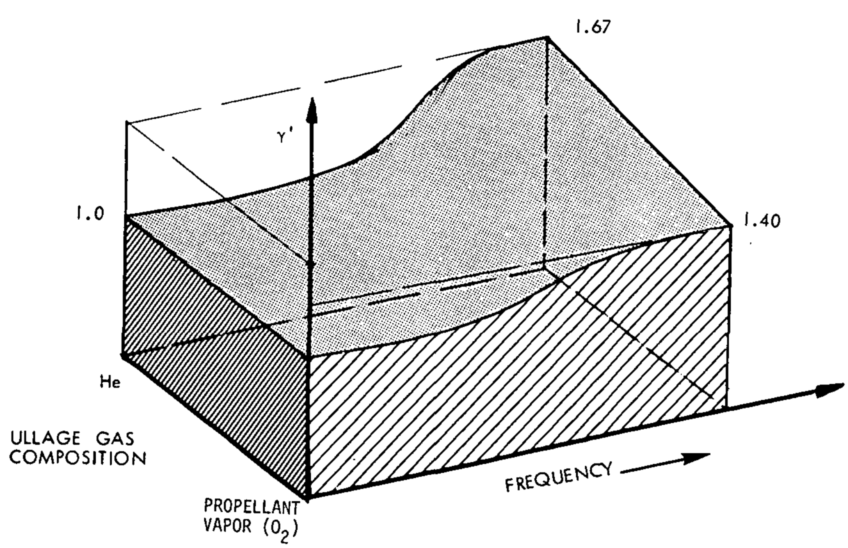

Figure 3-3. γ as a Function of RIGS Resonating Frequency and Ullage Gas Composition

measuring the percent change in the RIGS resonating frequency as a function of the ullage gas mix it was possible to obtain the effective gamma, and hence, the error in the propellant quantity measurement as a function of RIGS resonating frequency.

The tests indicate that the system in the frequency range of 0.5 to 3 Hz operates, as suggested in the previous paragraphs, more in the isothermal than adiabatic mode. The effective γ for air was measured to be 1.13 and for helium 1.22 (as compared to 1.4 and 1.67 for adiabatic conditions). Thus in extreme cases where the ullage gas is changed from pure helium to pure O_2 a 4% error in ullage volume measurement would result. However, for a more practical situation where the He/O_2 ratio varies by, say, 20%, the gauging error due to this cause would be well below 1%.

4.0 SENSOR DESIGN

Two RIGS sensors were built during the course of this program. Both sensors were strictly breadboards and no effort was made to optimize their size or minimize their weight. The first sensor, shown in Figures 2-3 and 4-1, was initially built with an aluminum case, but later was modified to have a Plexiglas enclosure so that the action of the follower bellows could be observed. The sensor used linear transformers (Clifton LTH-11-B-9 induction potentiometers) to provide the driver and follower position signals. The driver bellows were actuated by a DC motor and gear train through a crank drive.

The first sensor served primarily as a development prototype to develop suitable follower bellows as well as to learn about several of the more subtle aspects about the system operation. It also aided in the checkout and development of the control system.

The second sensor was constructed to correct several of the shortcomings of the first unit. A photograph of the second sensor is given in Figure 2-4. An assembly drawing of the sensor is given in Figure 4-2. As can be seen from the drawing, it incorporated "E" core driver and follower position pickoffs instead of the linear transformers used with the first model. Also jewel bearings and extensive provisions for balancing the follower balance arm were incorporated. The bellows were made out of rubber by a dip-molding process over an aluminum mandrel. The driver bellows were approximately 0.030-inch-thick. The follower bellows were approximately 0.017-inch-thick. A dc electric motor with an eccentric cam was used to actuate the driver bellows.

Referring to Figure 2-4 it is seen that an adapter flange is located between the propellant tank and the RIGS sensor. The purpose of this flange is to provide a mounting surface for the Teflon isolation bladder.

The RIGS sensor was assembled with "O" rings and bolted together so that it was air tight; however, external connections between the top, middle, and lower parts of the sensor were provided with tubing so that the pressure in all parts of the sensor would be equalized. It was found during tests that using approximately 6-inch-long, 1/4-inch-diameter tubing to interconnect the various parts of the sensor provided good pressure equalization but did not affect the performance of the sensor.

The major difficulty during the construction and development of the sensor was due to the follower bellows. Initially a rubber diaphragm of the type shown in Figure 4-1 was used; however, it never operated properly. Later after several unsuccessful attempts, bellows as shown in Figures 2-3 and 4-2 were developed. The bellows worked properly, but were very difficult to install and adjust. The major problem was that if they were made sufficiently rigid to be easily handled, they had a spring constant greater than 0.1 lb/inch and thus were too stiff. Bellows with spring constants below 0.1 lb/inch are very delicate and difficult to work with. Although with additional work a suitable bellows probably could be produced by incorporating stiffeners and webbs, the whole problem can be circumvented by going to the augmented RIGS design described in Section 7. The augmented RIGS should withstand a bellows spring constant on the order of several pounds per inch, thus allowing the use of metal bellows with much more predictable characteristics.

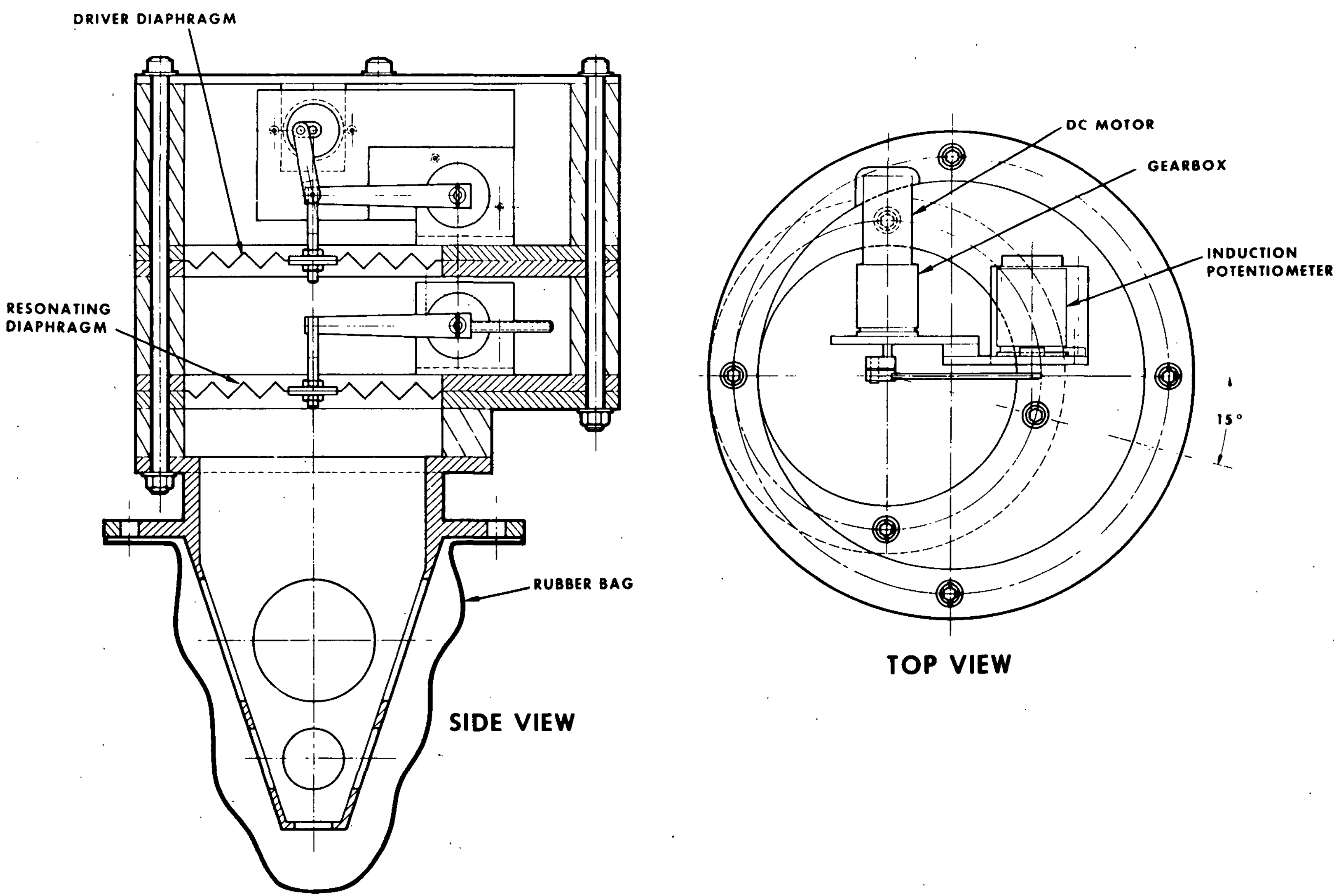

Figure 4-1. RIGS Sensor Assembly Drawing (First Sensor)

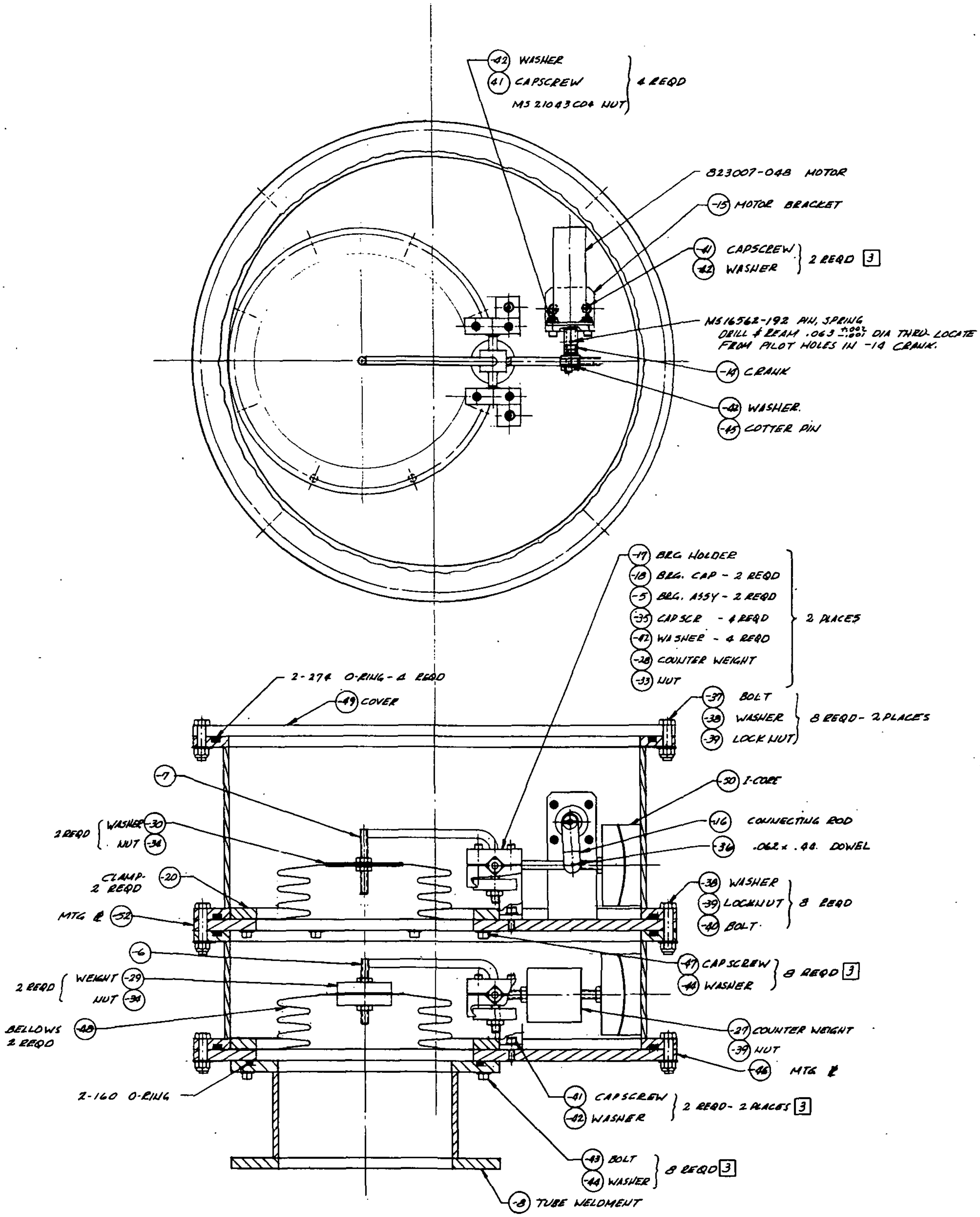

Figure 4-2. RIGS Sensor Assembly Drawing (Second Sensor)

5.0 ELECTRONIC SUBSYSTEMS

A block diagram of the RIGS control system is shown in Figure 5-1. The purpose of the driver and follower E-core transformers is to sense the position of their respective bellows. The E-cores are excited from a 400-Hz phase-shift oscillator that is shown in Figure 5-2. The output waveform of the E-cores is a 400-Hz sinusoidal wave that is amplitude-modulated by the motion of the bellows. The demodulators shown in Figure 5-3 remove the 400-Hz component thus leaving a DC voltage that is proportional to the displacement of the bellows. This DC voltage is amplified by the high gain amplifiers shown in Figure 5-4. The resulting square waves are used to trigger a flip-flop which is sensitive to the positive slope of the input signal, so that the driver sets the flip-flop, while the follower resets the flip-flop. The resulting flip-flop output waveform is a square wave whose width is proportional to the phase difference between driver and follower. Figure 5-5 illustrates the method used to compute the phase difference. The flip-flop output is integrated by an operational amplifier with an RC time constant of 10 seconds, which produces a DC voltage proportional to the phase difference. Referring to Figure 5-6 it is seen that the integrator output is compared to a stable reference voltage that represents the desired phase difference (reference phase). The difference between the reference phase and the actual phase difference produces a phase error voltage which is integrated by an operational amplifier having an RC time constant of 88 seconds, as shown in Figure 5-7. This integrated phase error voltage is applied to the motor driver which drives the motor in the appropriate direction to reduce the phase error voltage to zero, thus maintaining the desired reference phase. Due to the long time constants involved with the integrators, the system requires approximately 30 seconds to stabilize on the reference phase.

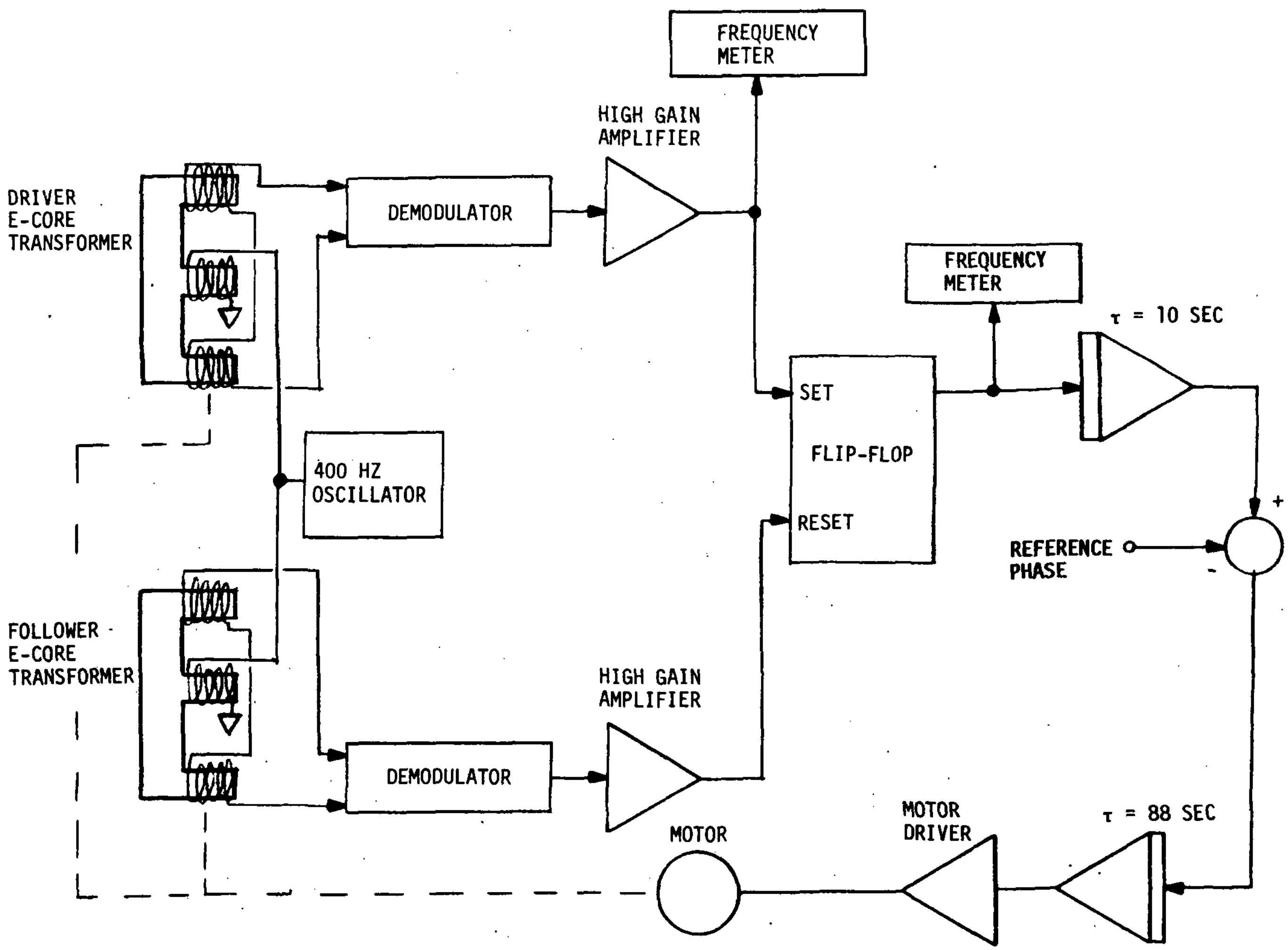

Figure 5-1. RIGS Control System Block Diagram

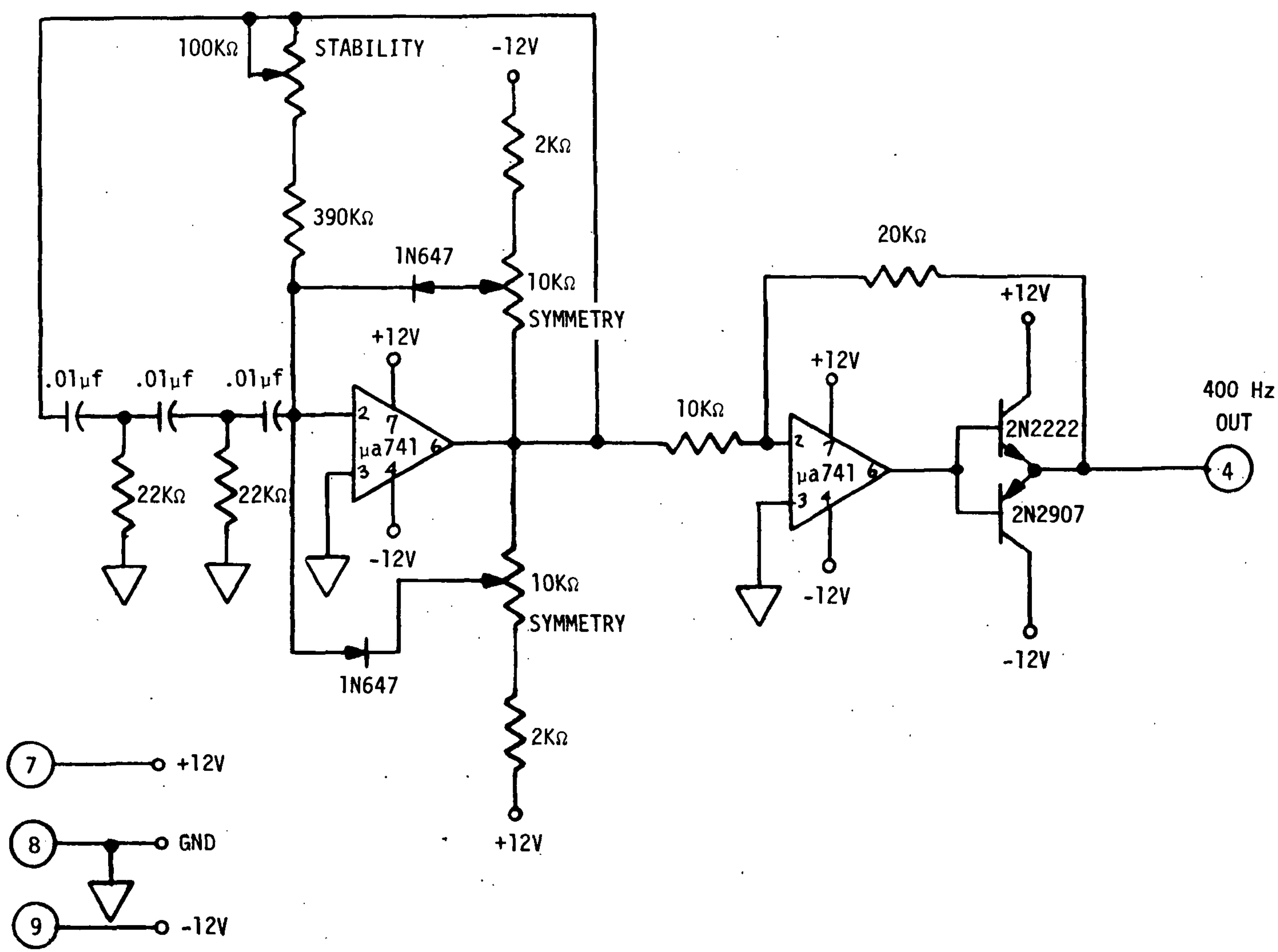

Figure 5-2. 400-Hz Oscillator and Power Amplifier

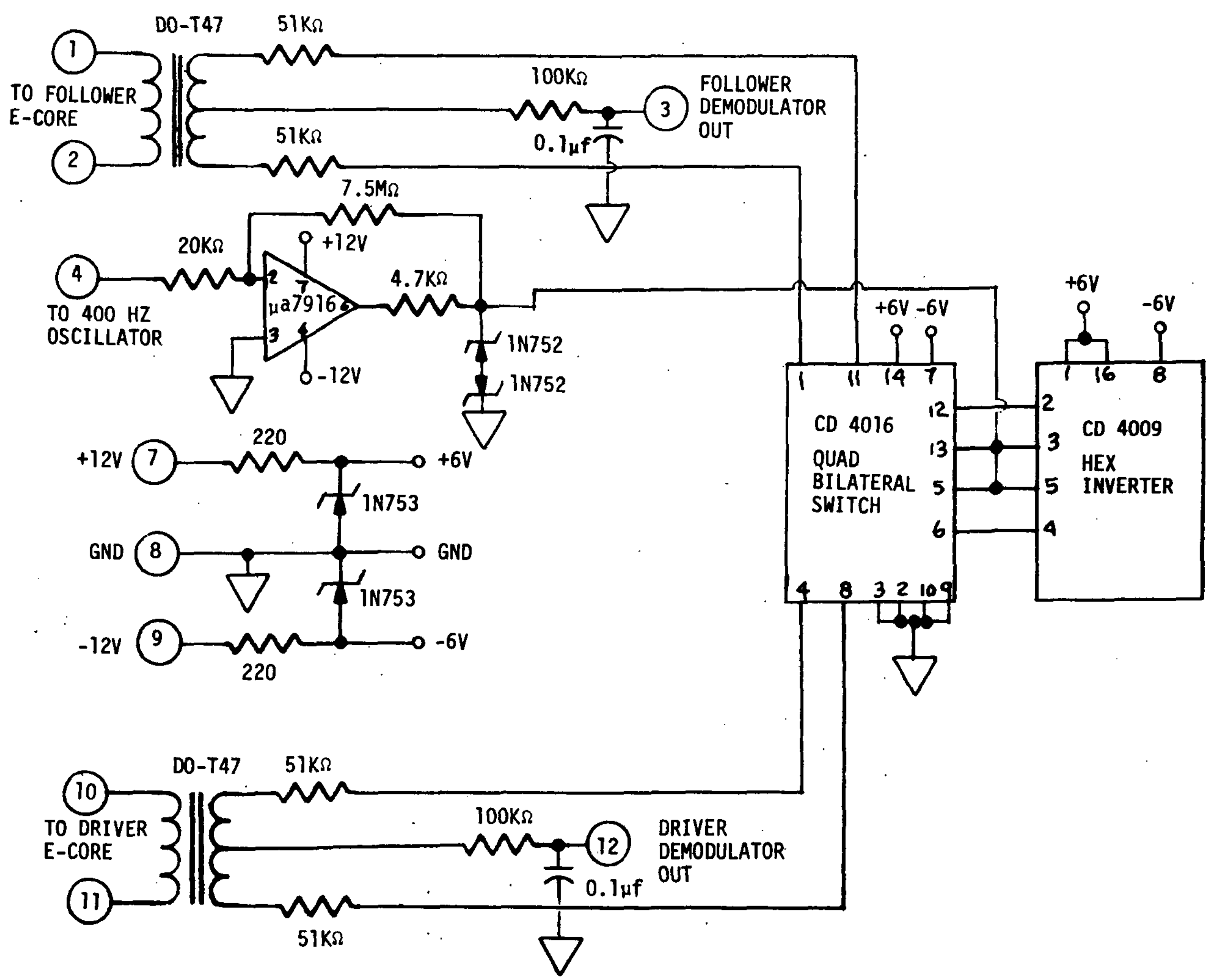

Figure 5-3. RIGS Demodulators

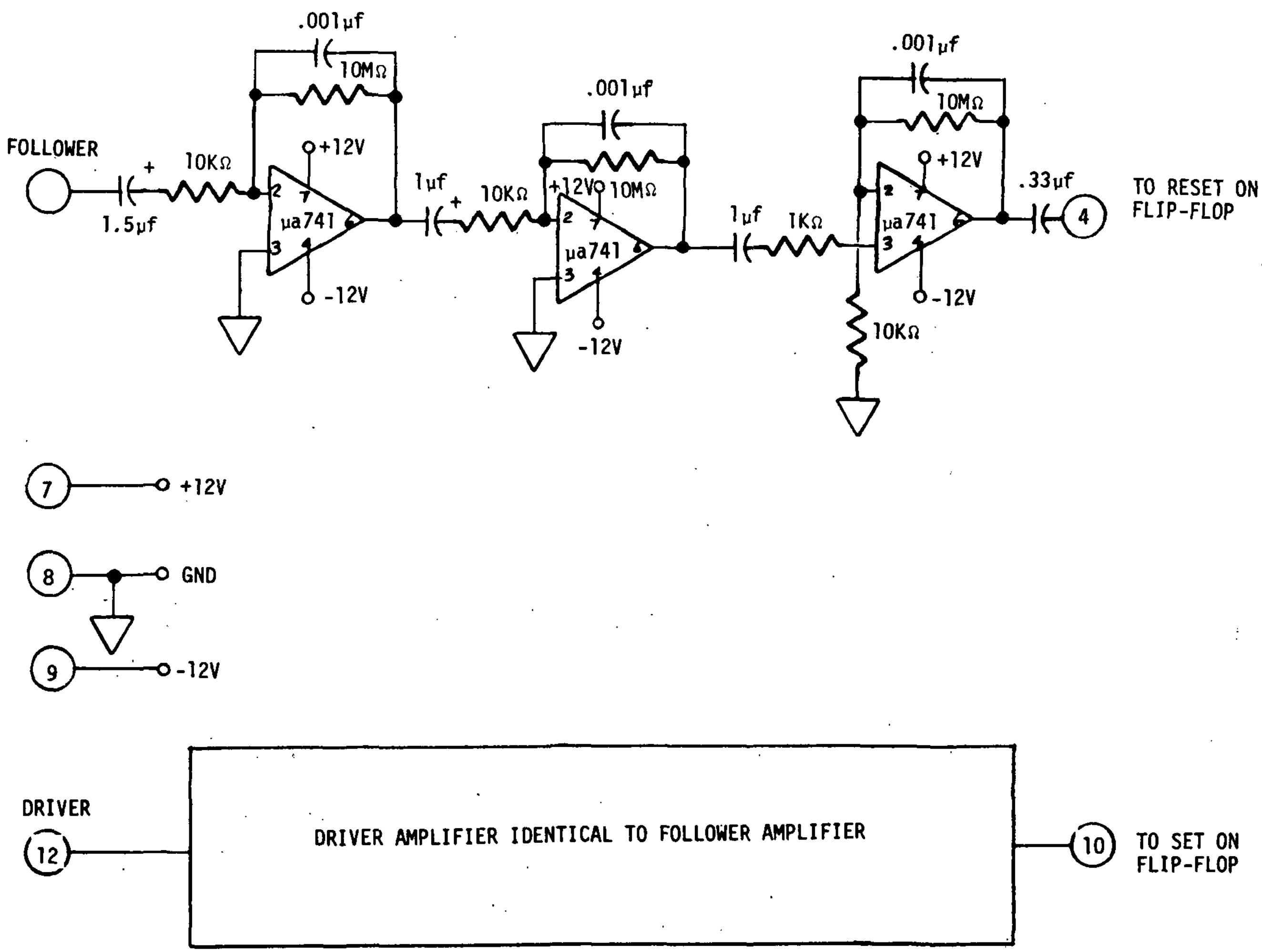

Figure 5-4. RIGS High Gain Amplifiers

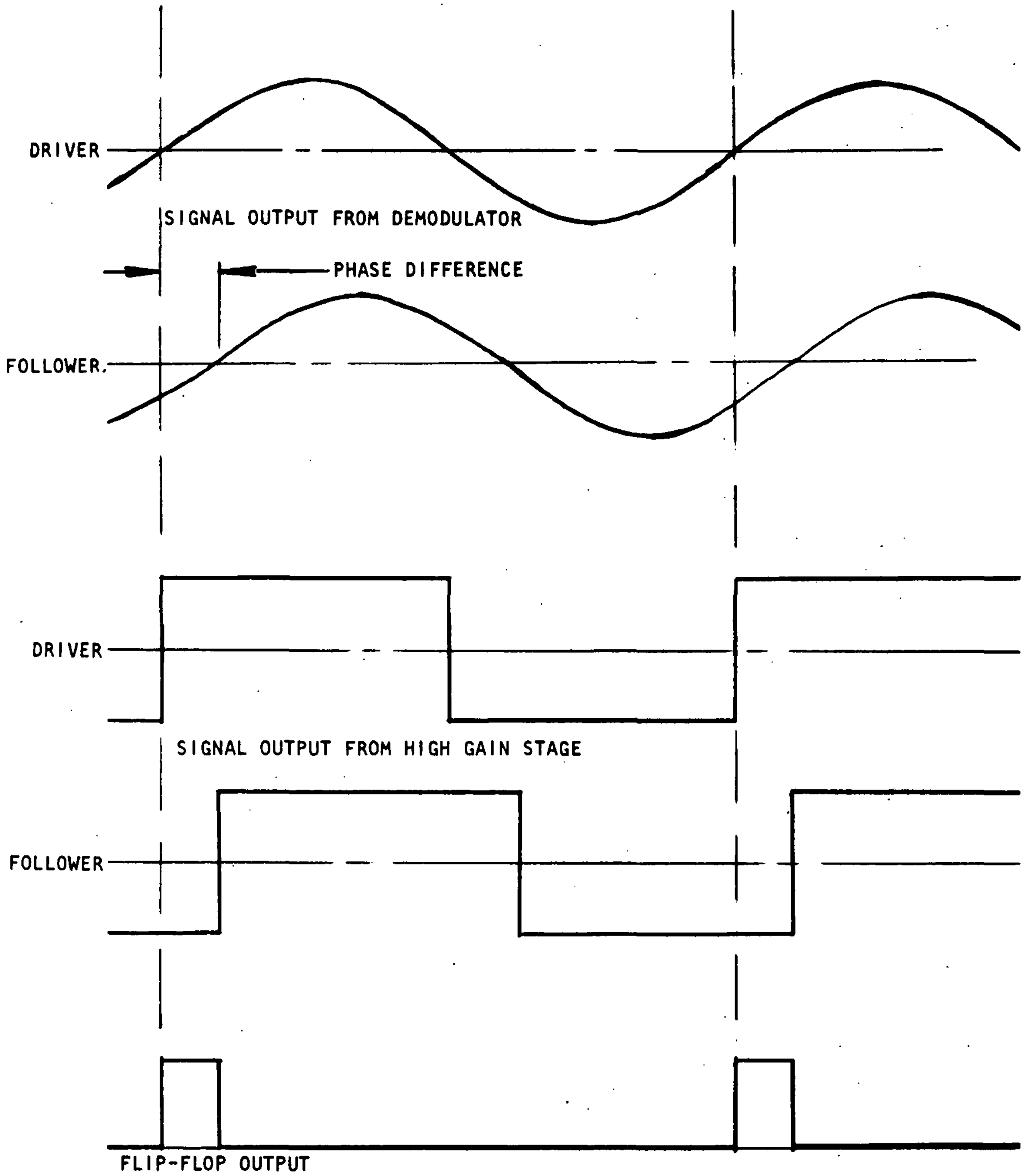

Figure 5-5. Illustration of the Method Used to Compute Phase Difference Between Driver and Follower Bellows

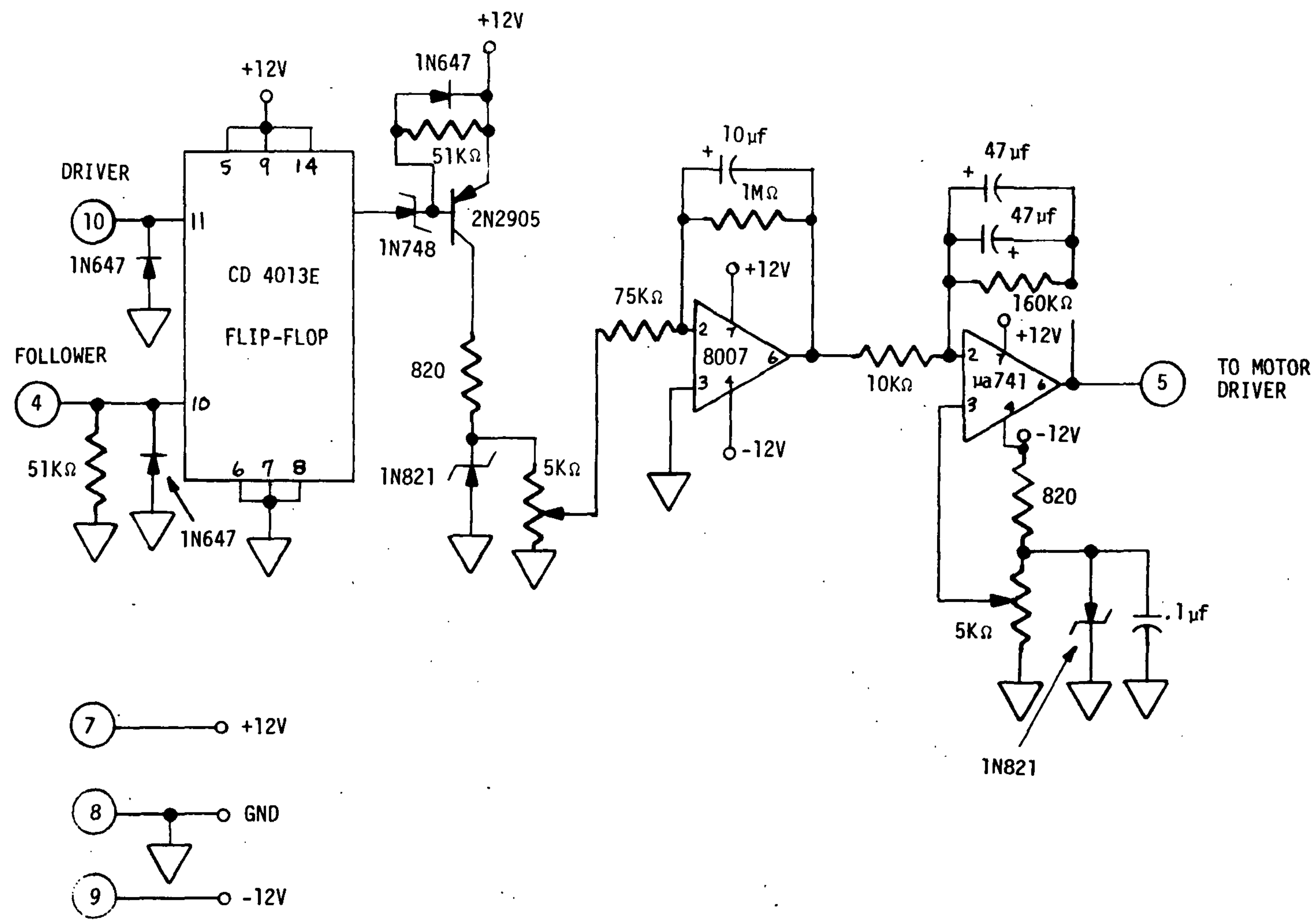

Figure 5-6. RIGS Flip-Flop, Integrator, and Phase Error Comparator

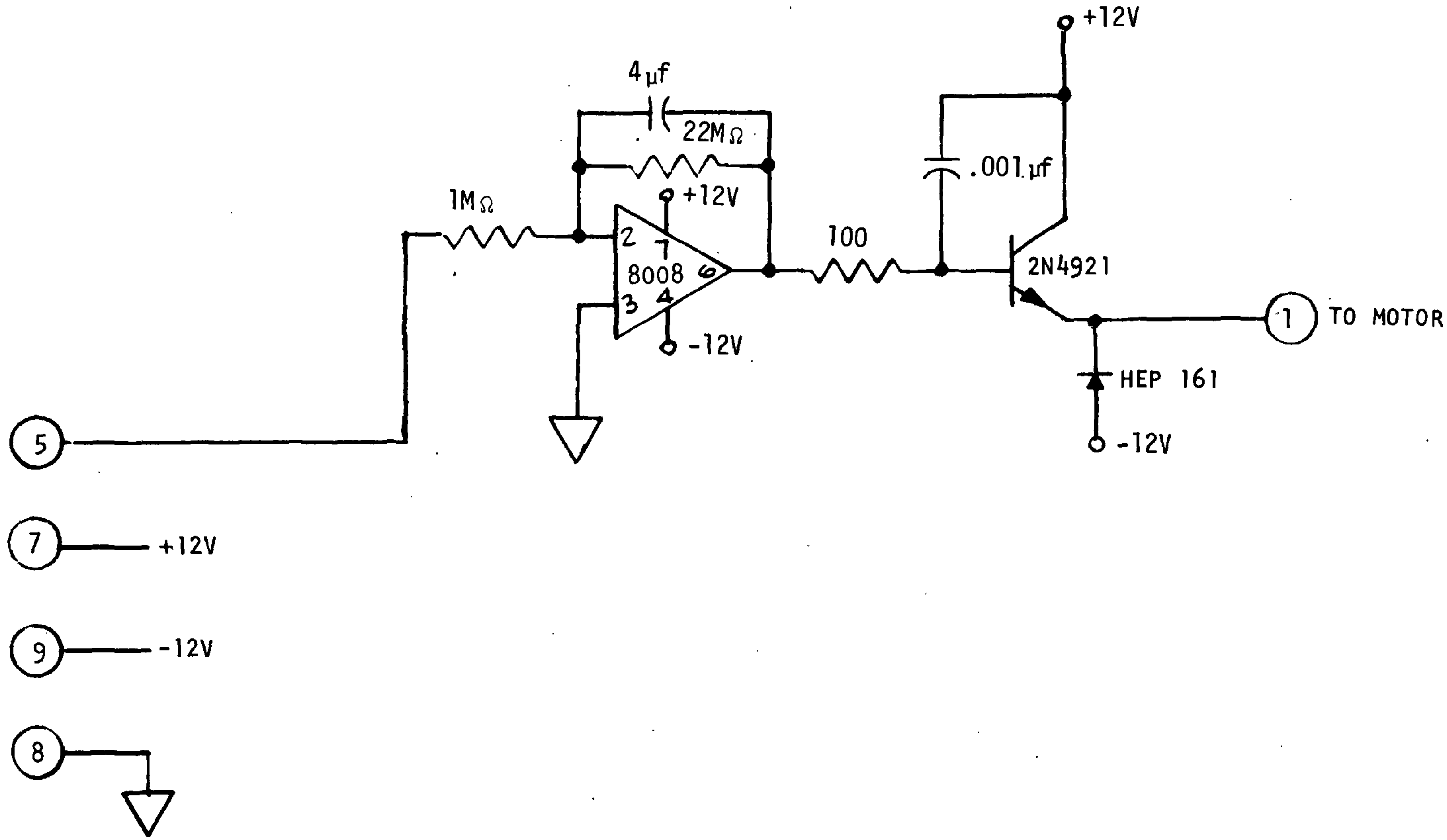

Figure 5-7. RIGS Motor Driver

6.0 RIGS TEST

The RIGS sensors were tested initially in the laboratory with an approximately 30-gallon tank using water to simulate the propellant. This tank was mounted on a gimbaling support so that the tank could be positioned right side up, on its side, or upside down. A photograph of the tank and sensor setup in the laboratory is shown in Figure 6-1. Later in the program a 100-gallon cryogenic tank was used first with water to simulate the propellant and then LN_2. A photograph of this tank during a test run is shown in Figure 6-2. After the LN_2 tests the sensor was mounted on a 110-gallon tank for additional system tests as well as to clear up some problems that were discovered during tests with the cryogenic tank.

In the beginning of the program the RIGS sensor was operated "open-loop." The frequency of the driver was set by adjusting the dc voltage to the motor. The resultant frequency was read off on an electronic counter. The lag (or lead) between the driver and follower piston was obtained with another counter using the driver signal to start it and the follower signal to stop. A block diagram of this test setup is shown in Figure 6-3.

Test data at each quantity of water in the tank were obtained by adjusting the motor speed to give a desired frequency and then reading off the resultant phase difference between the driver and the follower piston. Then the motor speed was changed and another data point obtained, etc. A typical curve giving the period of the driver frequency versus phase difference obtained this way is shown in Figure 6-4.

After the initial open-loop tests a control system that automatically adjusts the motor speed to give a desired phase angle was designed and built (see Section 5). Most of the system tests described in this section were performed using this control system and only occasionally was the open-loop method of operation employed for optimizing the phase angle.

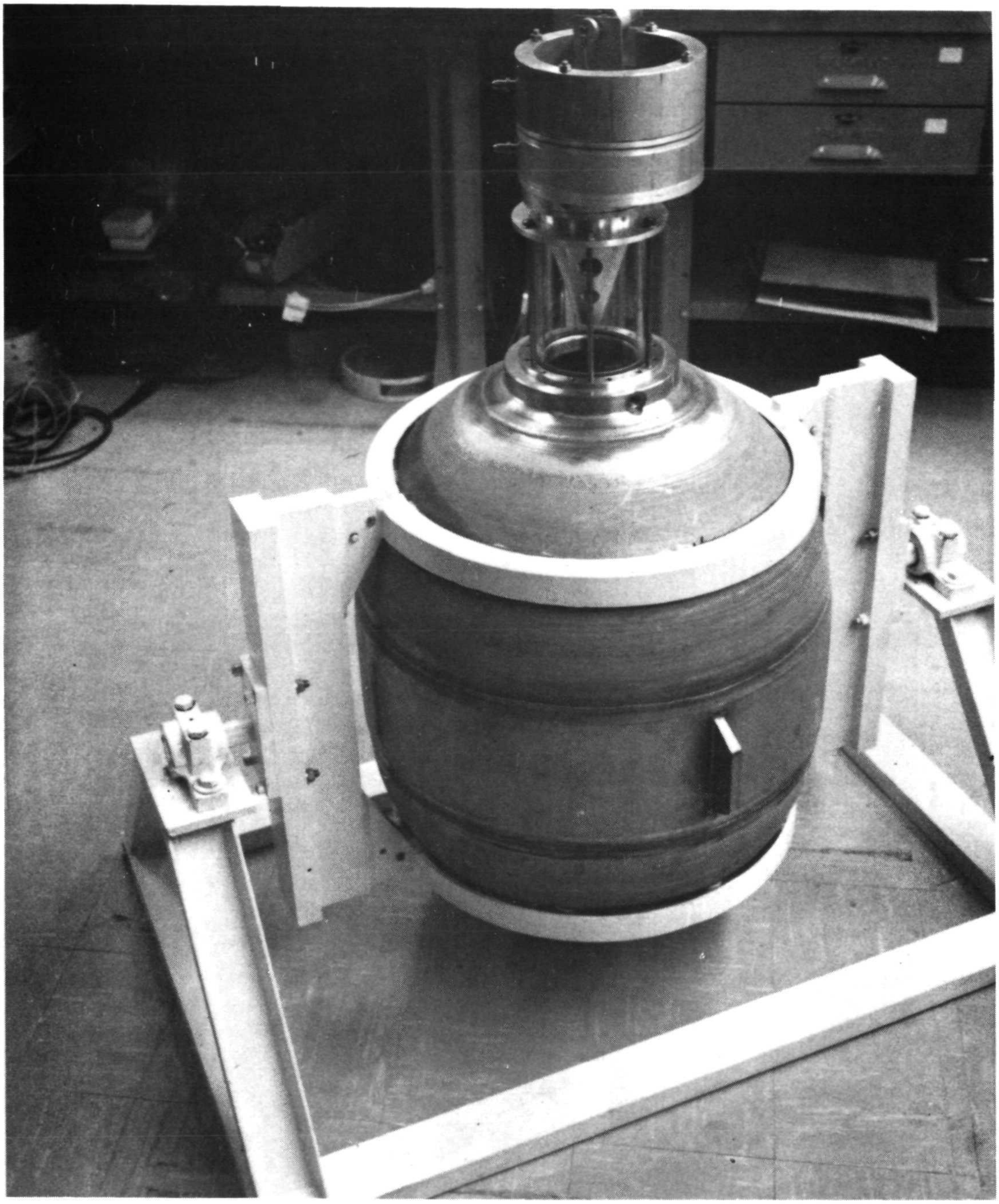

Figure 6-1. RIGS Tests in the Laboratory

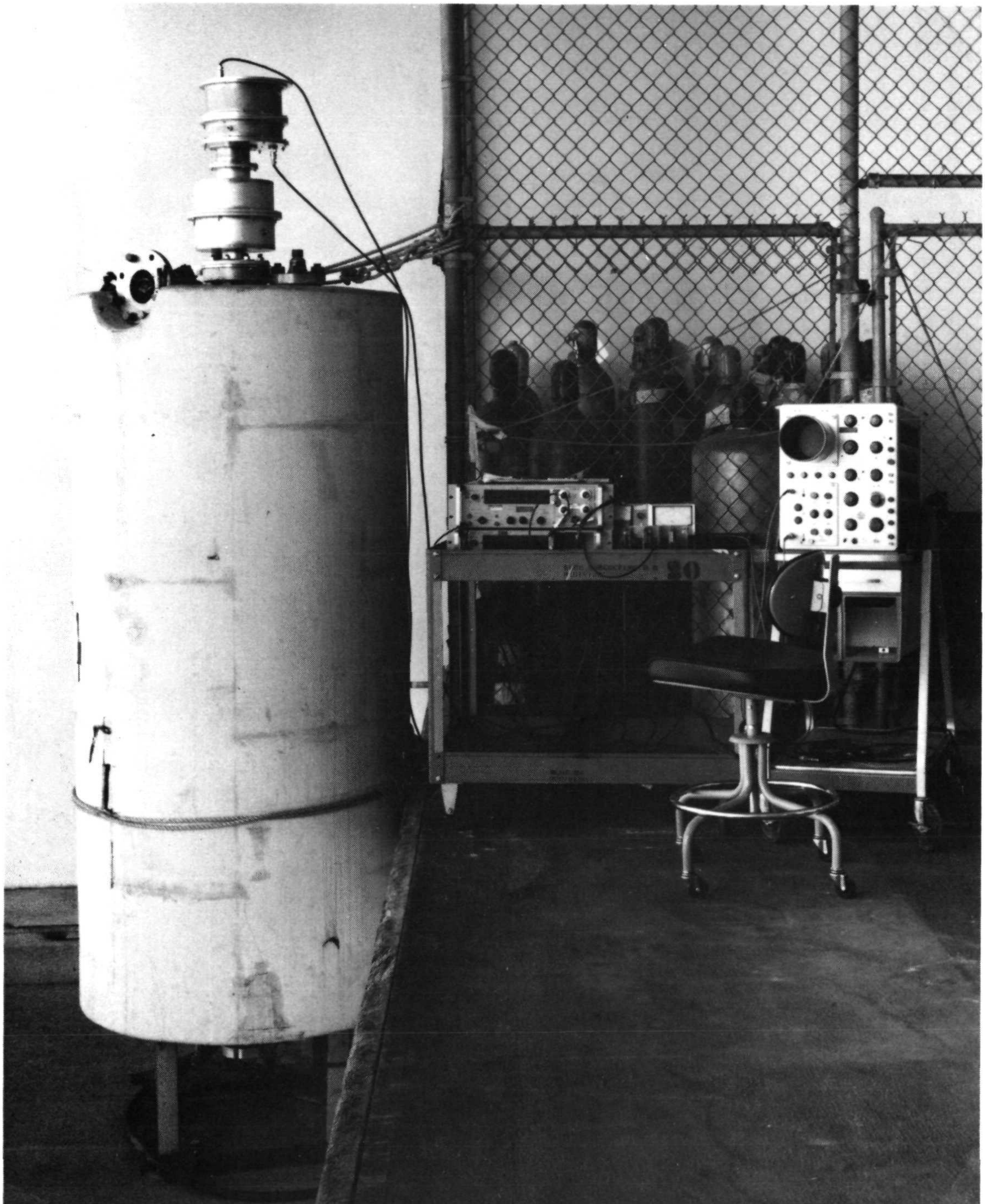

Figure 6-2. RIGS Test Setup with 100 Gallon Cryogenic Tank

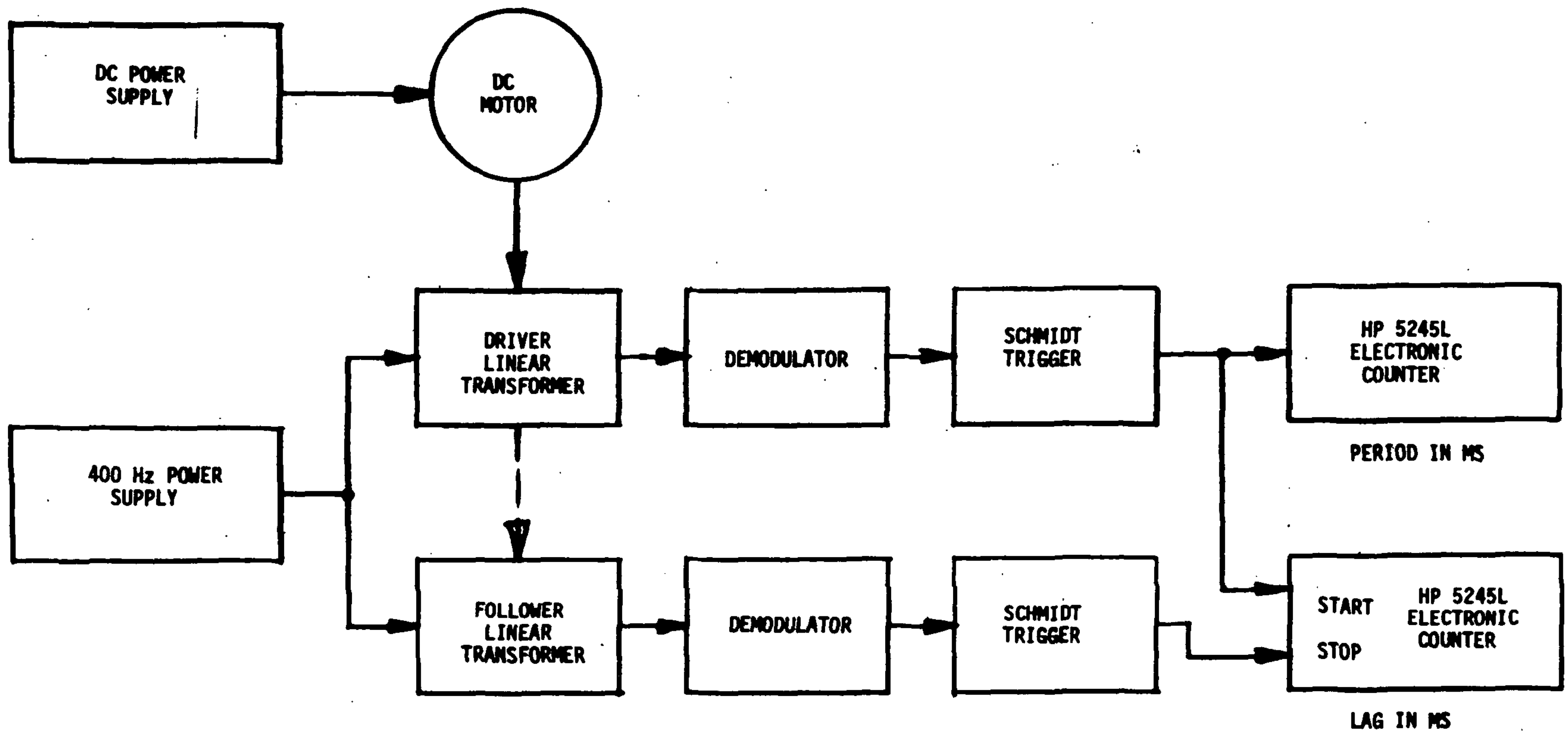

Figure 6-3. Block Diagram of RIGS Sensor Test Setup

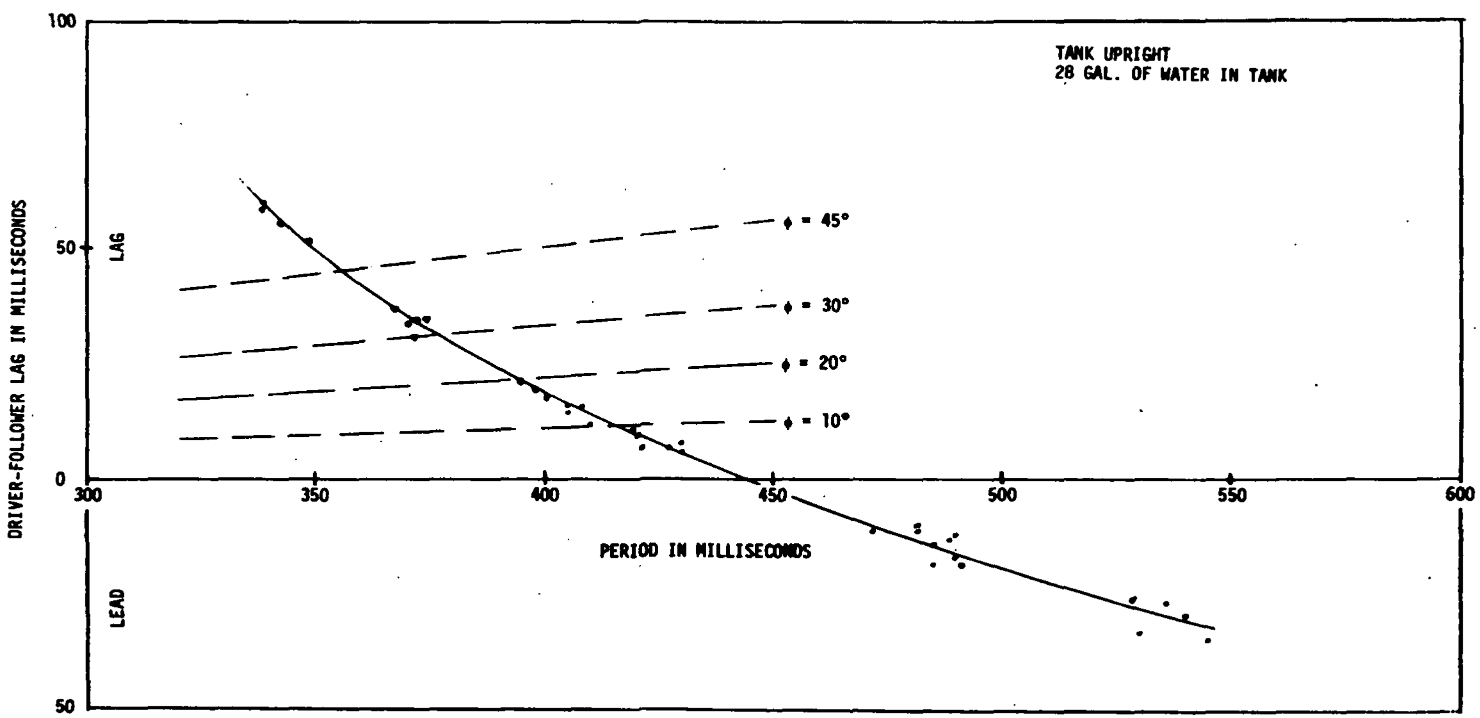

Figure 6-4. Typical Set of Test Data at 28 Gal of Water in Tank

The key objectives of the test program were:

1. To measure the effective ratio of specific heats (γ) as a function of RIGS resonating frequency and determine how much error in terms of propellant quantity measurement would result from changes in the He pressurant gas to propellant vapor ratio.

2. To see how much effect the surface tension propellant orientation devices have on the RIGS performance.

3. To evaluate, in general, how well the RIGS operates as a propellant gauging system.

The test results related to measurement of effective γ have been described in Section 3.0. In summary it was found that in the frequency range of 0.5 to 3 Hz the effective γ is 1.13 for O_2 and 1.22 for He. The error in propellant quantity determination due to changes in He/O_2 ratio will be 0.33 times the error predicted using adiabatic gas laws. In practical cases the absolute error in propellant quantity measurement should be less than 1.0% due to this effect.

Several surface tension devices were fabricated out of metal screens and tested with the RIGS sensor. The screens were made into the form of a tube and inserted into the tank through the opening as shown in Figure 6-5 so that the pressure wave from the RIGS sensor had to be transmitted through the screen into the surrounding ullage volume. Dry screens had no measureable effect on the RIGS resonating frequency. When the screens were made wet by dipping them into water there was a tendency for the sensor to temporarily increase the resonating frequency by a few percent; however, not long enough to get good quantitative data. In all cases the resonating frequency stabilized at the original (no screen or dry screen) value in a short time, probably when sufficient dry holes opened up in the screen.

Typical RIGS performance data obtained early in the program with the 30-gallon tank are given in Figure 6-6. As can be seen from the figure the frequency (period) variation with propellant quantity in the tank followed very closely the predicted values. The overall gauging accuracy typically ranged between 1 and 2 percent. After the tests with the 30-gallon tank the sensor was mounted on a 100-gallon cryogenic tank and tests were

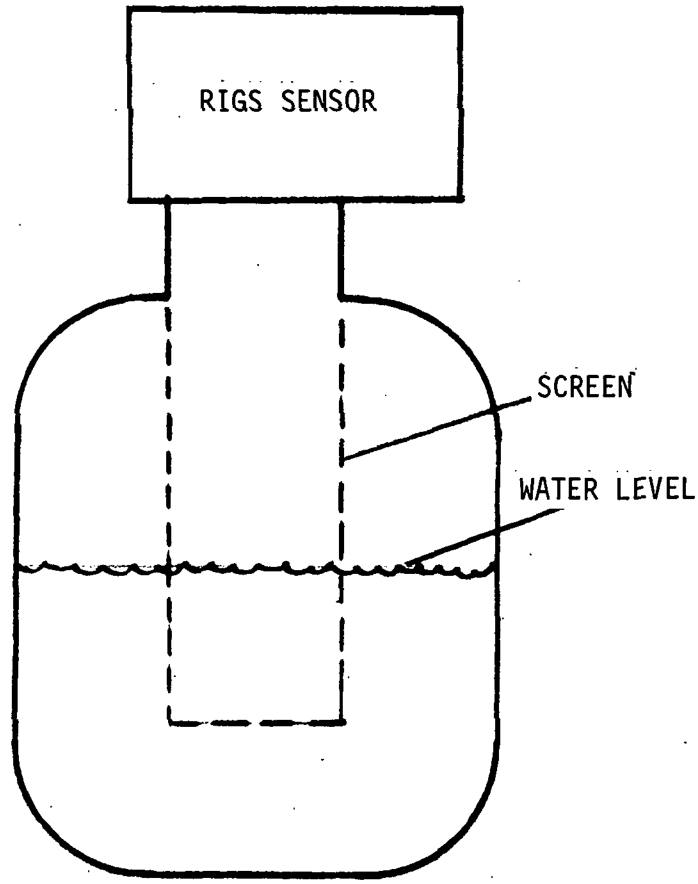

Figure 6-5. RIGS First Setup with Surface Tension Screens

conducted with water and then LN_2 to simulate the propellant. At the close of the program the sensor was mounted on a 110-gallon tank where, as mentioned in Section 2.0, this accuracy was improved to below one percent.

During tests with the 100-gallon cryogenic tank the gauge operated properly between full and approximately 50 gallons. However, if more water was drawn out, the resonating frequency did not follow the predicted values but was consistently higher by a few percent as well as being rather unstable. (Near tank-empty conditions a one percent error in the resonating frequency determination produces roughly a ten percent error in the propellant quantity determination). The problem, at that time, was attributed to the long and relatively small diameter tubing connecting the sensor to the tank. The data obtained with LN_2 indicate that the sensor behaved substantially the same as it did with water.

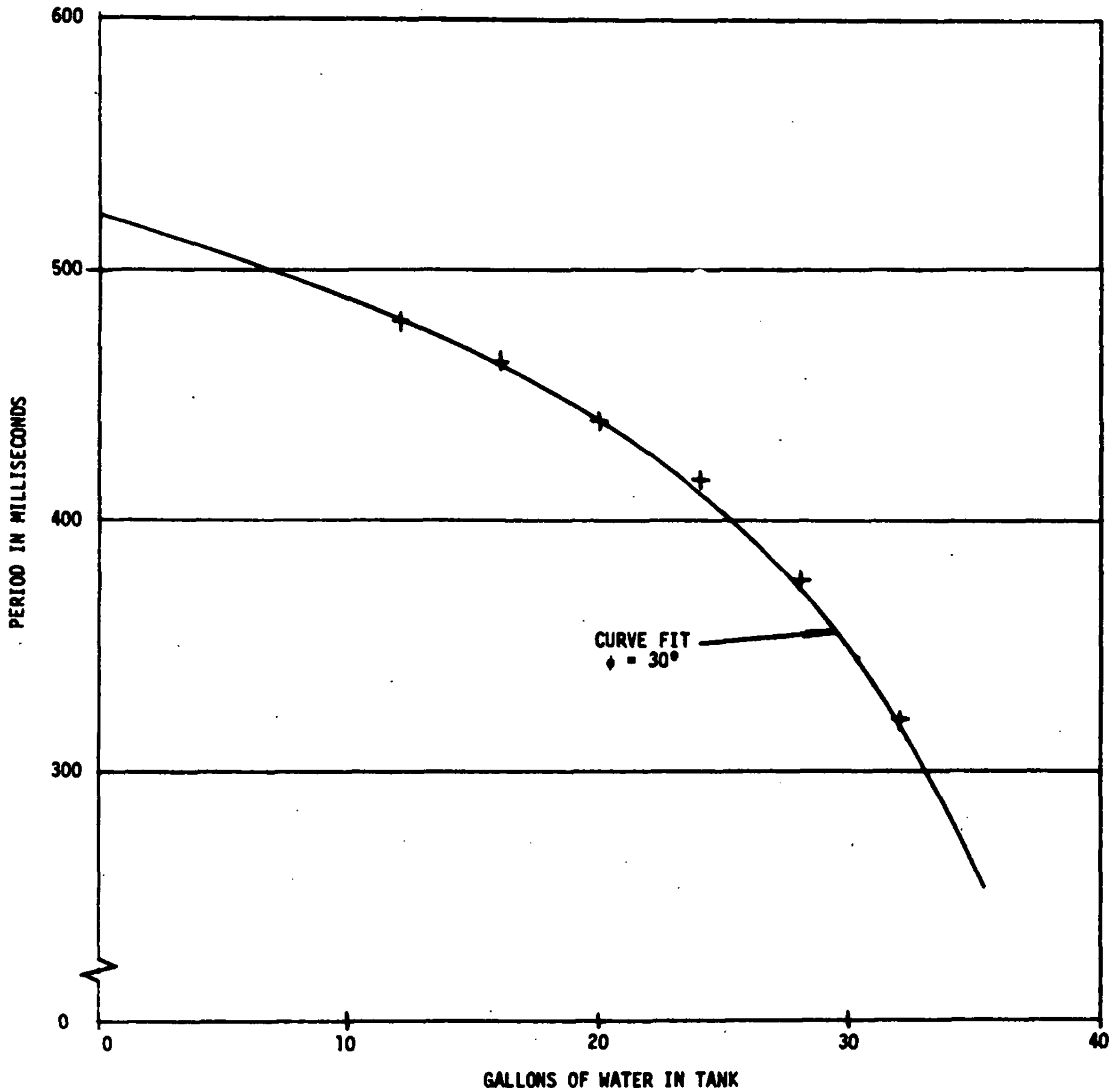

Figure 6-6. RIGS Sensor Test Data

After completing the tests with liquid nitrogen the gauge was brought back to the lab and installed on a 110-gallon tank (two 55-gallon drums welded together) for additional tests and to investigate why it failed to work properly with an ullage volume greater than 50 gallons. Initially the sensor behaved very much like it did with the cryogenic tank and disproved the hypothesis that the tube connecting the sensor to the tank was the cause of the problem.

After initial unsuccessful attempts to make the system perform properly, the sensor was disassembled and the counterbalance weights increased to ∿1 lb, to decrease the resonating frequency. Test data obtained with this configuration are given in Figure 2-6 and showed that the sensor operated properly and as predicted by theory throughout the complete range.

The reason why the sensor did not appear to work with the smaller 1/2-lb weights but did well with the 1-lb weights was found to be due to a minor (and up to that time undiscovered) malfunction of the control system combined with the particular data acquisition technique that was used.

A typical plot giving the sensor resonating frequency as a function of time (with a constant ullage volume) is given in Figure 6-7. The disturbances shown in Figure 6-7 occurred at random intervals and were caused by the flip-flop in the control system either setting prematurely or failing to reset thus causing a large phase error input into the control system, which increases the motor speed and, in turn, sets the sensor into a search pattern. It takes on the order of 20 to 30 cycles for the sensor to settle out on the correct period. Since this intermittent malfunction of the flip-flop occurs very rarely at ullage volume below 50 gallons, it went undetected during laboratory checkout of the sensor with the 30-gallon tank; however, with an ullage volume greater than 50 gallons, it occurs more frequently, on the order of once a minute, and tends to increase the average resonating frequency by a few percent. Since the data were obtained by averaging 100 periods with a counter, the resultant period was consistently low and provided a source of error as well as scatter in data points. When this effect was noticed during tests with the 110-gallon

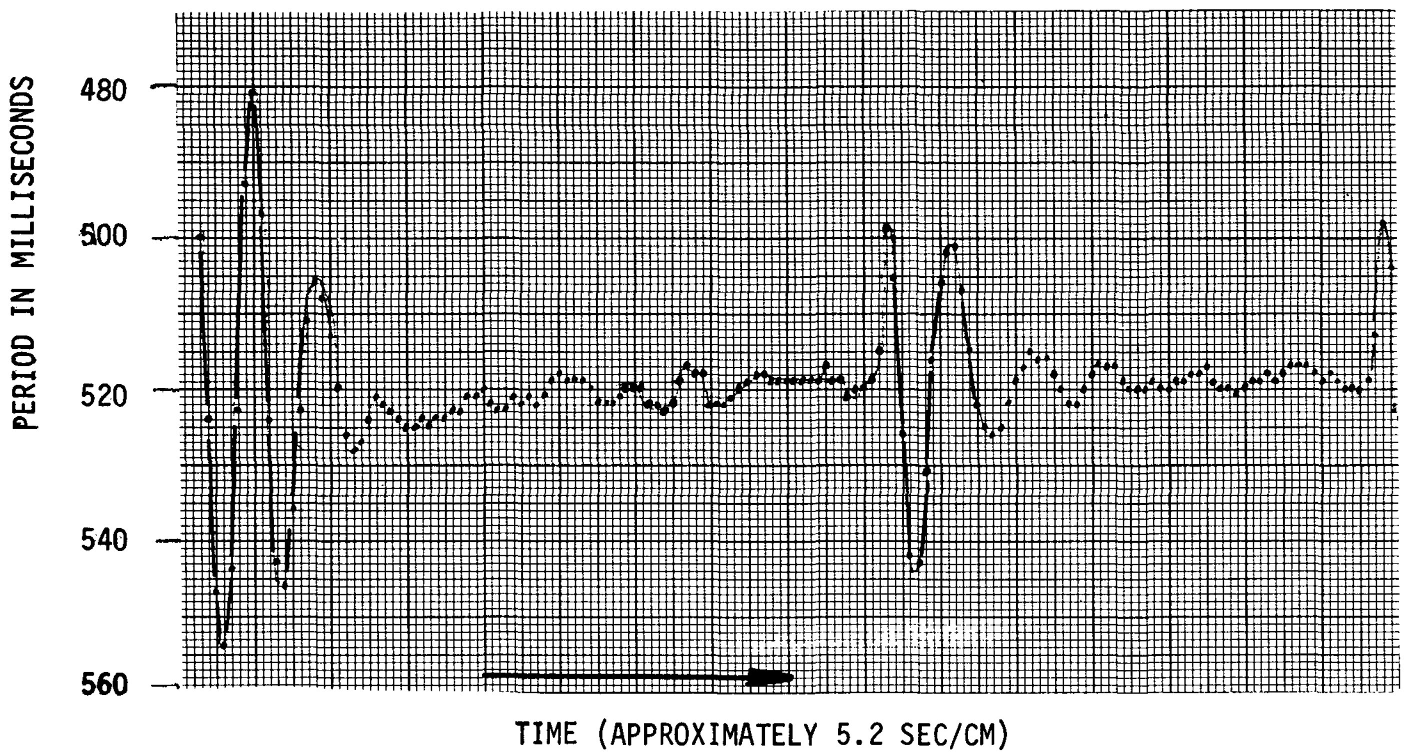

Figure 6-7. Effect of Disturbances in RIGS Resonating Period

tank in the lab, the data acquisition technique was changed to plotting several averages of ten periods (which were read off by a counter) and choosing the period that occurred most frequently while ignoring the points that fell considerably below or above the average. Typical plots of periods for several water quantities in the tank are shown in Figure 6-8.

These disturbances would not affect the system significantly if the sensor would settle out at the correct frequency more rapidly than it does. The current system was designed without a damping loop and therefore was considerably underdamped (as can be seen from the plot in Figure 6-7). Incorporating a feedback element in the motor would provide the necessary damping and thus reduce the oscillations. Also, of course, fixing the intermittent flip-flop failures (which turned out to be an extremely elusive task) would greatly reduce the frequency of the disturbances.

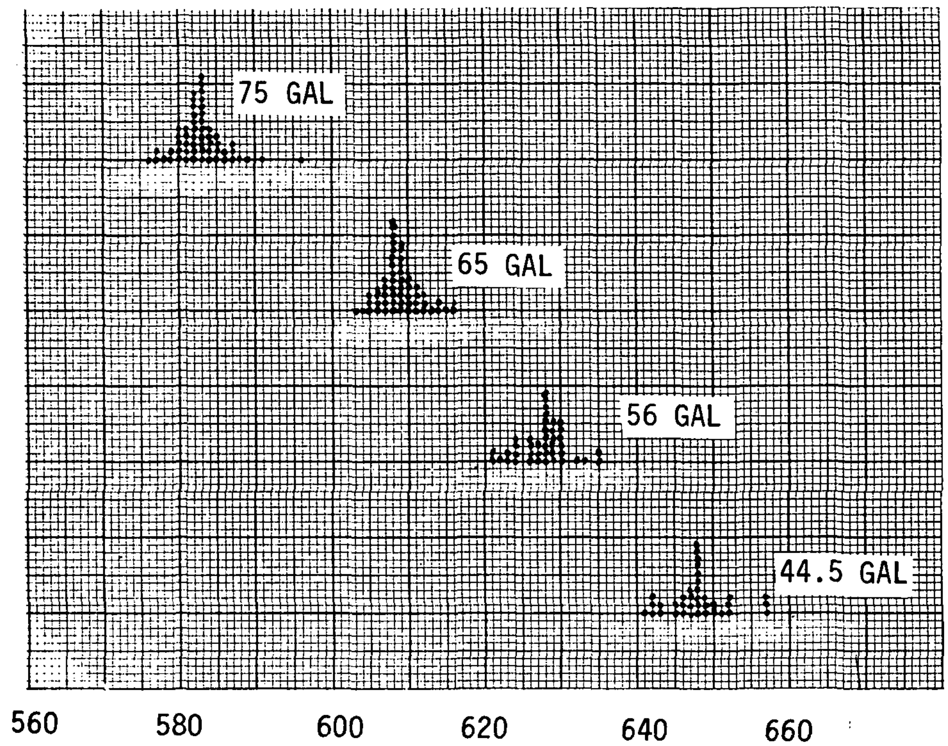

Figure 6-8. Illustration of Data Acquisition Technique Used During RIGS Tests

Data obtained by the method shown in Figure 6-8 were curve fitted to an optimum curve (sixth order polynomial) using a computer program. This curve, together with test data and deviations of test data from this curve are shown in Figure 2-6. The same data were also compared to the theoretical curve of the form

$$\frac{1}{P} = \sqrt{\frac{k_1}{(V_o - V_F)} + k_2} \tag{6-1}$$

where k_2 represents bellows spring constant (K_B/M), and k_1 represents the spring constant parameters of the ullage volume $\left(\frac{A^2 \gamma P_u}{M}\right)$

The bellows spring constant was measured by lifting the sensor off the tank (so that the ullage volume (V_o) appears to be infinite) and determining its resonating frequency. The spring constant parameters of the ullage

volume were derived from resonating frequency measurements at small ullage volumes.

The resultant curve is shown in Figure 6-9 and shows a good agreement between the test data and theory. The slight deviation between the two can easily be explained as second order effects which are not taken into account by the relatively unsophisticated form of Equation (6-1). Therefore, as might be expected, to assure gauging accuracies of better than one percent a calibration curve of the type shown in Figure 2-6 should be utilized.

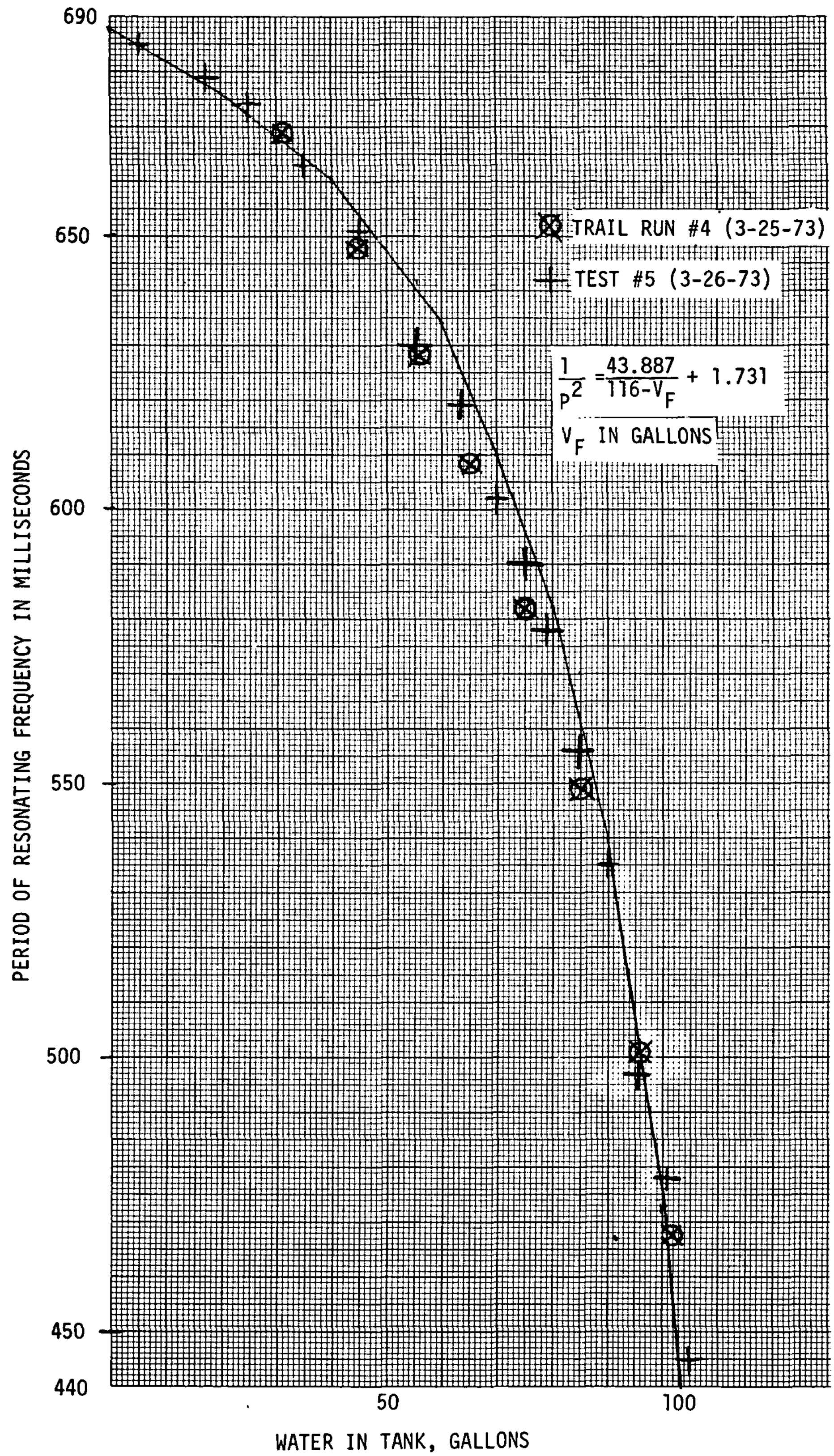

Figure 6-9. RIGS Test Results Compared to a Theoretical Curve

7.0 CONCLUSIONS AND RECOMMENDATIONS

As described earlier, the RIGS in the configuration used during the course of this program has several significant disadvantages:

1. The follower bellows require a spring constant on the order of 0.1 lb/inch. To obtain this low a spring constant, the bellows are flimsy and difficult to handle and install.

2. For the RIGS to operate properly the bellows requires a mass on the order of one pound. Another pound is required at the end of the follower beam to counter-balance the weight on the bellows. This makes a total follower piston beam weight on the order of 2 lbs, all supported by jewel bearings. It would be difficult to construct such a beam and bearings strong enough to operate during acceleration and vibration of the launch environment.

3. The existing RIGS control system is too slow for use during transient conditions.

It is proposed to correct the first two problem areas by augmenting the RIGS sensor with an electronic subsystem which simulates the mass on the follower piston. The ullage volume of the tank would resonate with an electronic circuit instead of a physical mass. The augmented RIGS also allows the use of much stiffer follower bellows without affecting the resonant frequency of the system. By use of a torquer and associated electronic subsystem, stiff bellows (with a spring constant on the order of several pounds per inch), would appear to have a very low, or even zero, spring constant.

The last problem area, the RIGS control system response time, is readily corrected by redesigning a part of the electronic control system.

7.1 Description of the Augmented RIGS

The augmented RIGS simulates the mass on the bellows by electronic means. It also can compensate for a relatively large spring constant in the bellows and make it look like a low spring constant. This is accomplished by incorporating an electromagnetic torquer on the follower

piston balance beam. The torquer applies an external force to the follower bellows making it look as if the bellows were loaded with a large mass. The force that is required to be exerted on the bellows can be derived from Equation (3-4) in Section 3.

$$M\ddot{x} + \left(\frac{A^2\gamma P_u}{V_u} + K_B\right)x = 0 \tag{7-1}$$

Now assume that the bellows physically has a small mass m and a relatively large mass M is added externally by force F(x) through a torquer. Then Equation (7-1) is rewriten as

$$(m + M)\ddot{x} + \left(\frac{A^2\gamma P_u}{V_u} + K_B\right)x = F(x) \tag{7-2}$$

and F(x) required to simulate a large mass (m + M) is $M\ddot{x}$.

By making the torquer force $F(x) = M\ddot{x} - K^1{}_B x$ Equation (7-2) becomes

$$(M + m)\ddot{x} + \left(\frac{A^2\gamma P_u}{V_u} + K_B - K^1{}_B\right) = F(x) \tag{7-3}$$

Now if the force applied by the torquer is equal to and opposite to the spring force of the bellows such that $K_B = K^1{}_B$, no matter what the actual bellows spring constant is, (within the torque capabilities of the torquer) it may be made to look like zero, or whatever value is desired. Preliminary estimates show that the torque requirement for the torquer is on the order of 12 in/oz, which can be provided by a relatively small and "off-the-shelf" unit such as Clifton D-1500-C-2.

A block diagram of the augmented RIGS sensor and associated control system is given in Figure 7-1. In all other respects the RIGS sensor operation would remain unchanged.

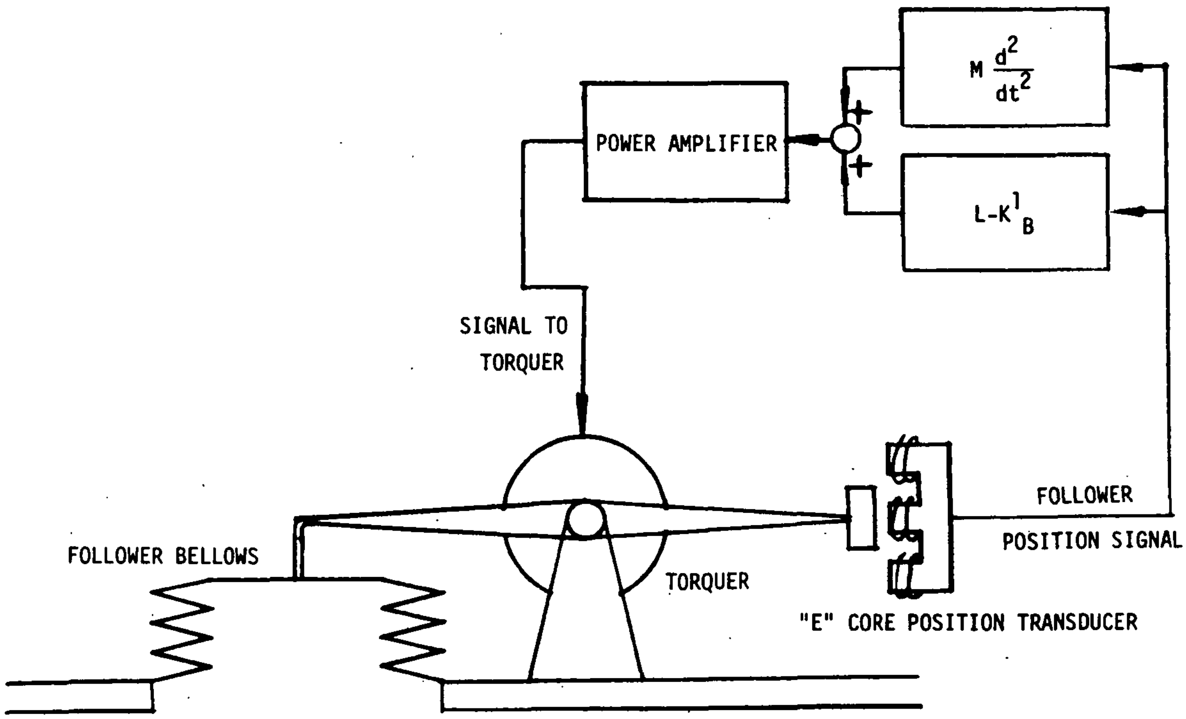

Figure 7-1. Augmented RIGS Block Diagram

7.2 Recommendations for Further Development of RIGS

The objective of the program described in this report was to construct a RIGS sensor based on the analyses performed during an earlier phase, and perform tests with it. This was successfully accomplished. However, the RIGS has changed sufficiently during the course of this program from the original concept so that additional analysis, especially the control aspect of it, will be required before further progress can be made. Also some analysis will be required to design and incorporate the augmented RIGS concept. Thus the next logical step is to construct a mathematical model of the present configuration of the RIGS sensor, including the augmented RIGS feature, optimize it, and, if necessary modify the existing sensors to include the latest changes. The following work statement is proposed for the next phase of RIGS development.

WORK STATEMENT

1. RIGS DESIGN

   a. Derive a mathematical model of the RIGS sensor.

   b. Using the mathematical model optimize the various system parameters such as bellows area, bellows spring constant, optimum bellows mass, torquer characteristics, etc.

2. DESIGN

   a. Design and incorporate the augmented RIGS feature into the sensor.

   b. Incorporate changes into the sensor that result from system optimization in Task 1b.

   c. Redesign the RIGS control system to have a response time of less than 10 seconds.

3. FABRICATION

   a. Modify the existing sensor and control system to include the design changes of Task 2.

   b. Construct suitable isolation diaphragm for use in LOX.

4. TESTS

   The Augmented RIGS will be tested in accordance with the original RIGS as contained in Section 2e, Exhibit "A", Scope of Work, Contract NAS8-28574, and analysis of test data performed in accordance with Section IIf of same Scope of Work.

5. REPORT

   Reports will be furnished in accordance with Section III, Exhibit "A", Scope of Work, NAS8-28574.